Spin dynamics in nonhomogeneous magnetic structures

김갑진
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❖ Outline

Brief introduction

- Spintronics

Spin dynamics?

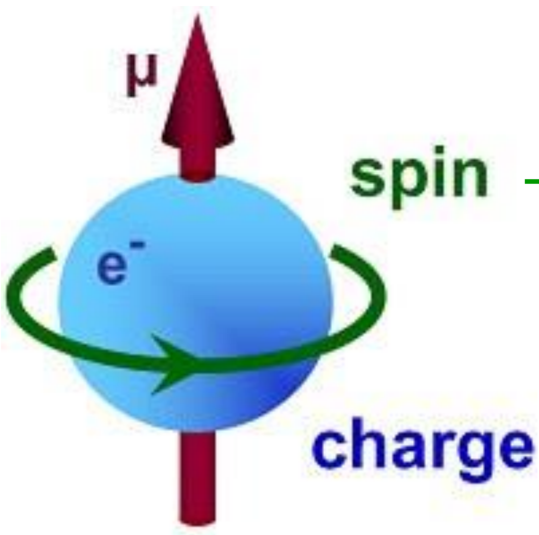
- By magnetic field
- By spin transfer toque
- By spin orbit torque

Some spin dynamics phenomena

- Ferrimagnetic spin dynamics
- Topological spin objects
- THz magnon

Summary and Prospect

❖ Spintronics = Electronics + Magetics



→ Magnetic properties

→ Electrical Properties

What happens if the electron moves?

❖ Spintronics = Electronics + Magetics

Flow of charge= current

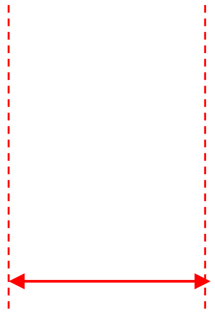
Flow of spin= ?

The study on the “moving spin” → “spintronics ”

❖ Why now?

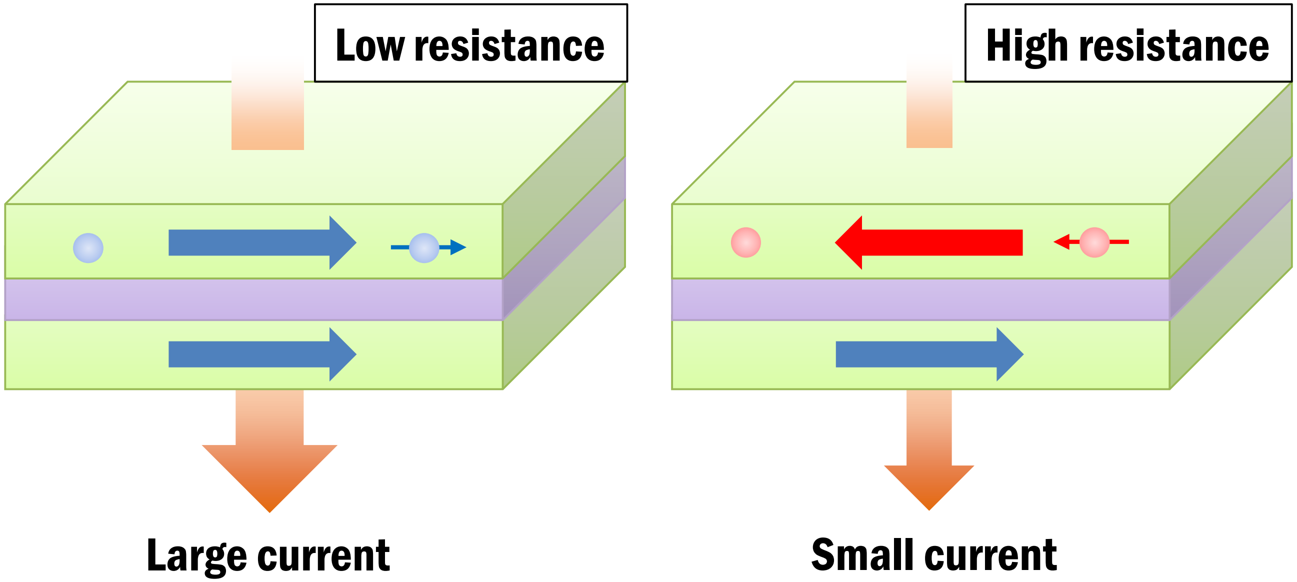
"spin" was already known at 100 years ago.
Then, why the "flow of spin" becomes main topic only now?

Spin is not preserved.
→ Difficult to define the "flow", but…



If the device is smaller than this?

❖ Discovery of giant magnetoresistance



Parallel → low resistance
Antiparallel → high resistance
→Giant Magnetoresistance (GMR)

Spin plays an important role!

❖ Discovery of giant magnetoresistance

9 October 2007

KUNGL.
VETENSKAPSA
THE ROYAL SWEDISH ACA

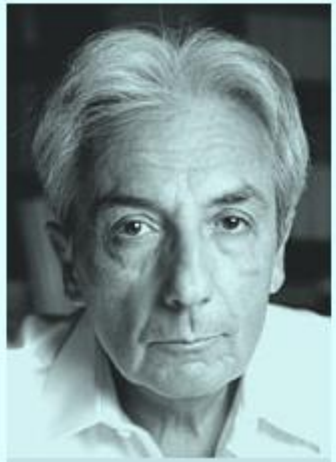


Photo: B. Fert, Invisuphoto

Albert Fert

1/2 of the prize

France

Université Paris-Sud;
Unité Mixte de Physique
CNRS/THALES
Orsay, France

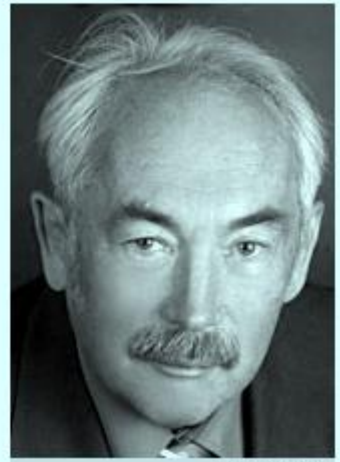


Photo: ©
Forschungszentrum Jülich

Peter Grünberg

1/2 of the prize

Germany

Forschungszentrum Jülich
Jülich, Germany

Scientif 2007

The Discovery of Giant Magnetoresistance

compiled by the Class for Physics of the Royal Swedish Academy of Sciences

❖ Newly discovered phenomena

(year) → demonstrated by experimentally

Fundamental mechanism		phenomena
Spin dependent scattering	→	Giant magnetoresistance (1989) → Nobel prize in physics 2007
Spin dependent diffusion	→	Spin pumping effect (2002)
Spin dependent thermal conductivity	→	Spin seebeck effect (2008), Magnon Hall effect (2010)
Spin orbit interaction	→	Spin Hall effect (2004), Rashba effect (2010 in metal), spin Hall MR (2012)
s-d exchange interaction	→	Spin transfer torque (2000), Spin-flip in cold electron (2015)
Antisymmetric exchange interaction	→	Interfacial Dzyaloshinskii-Moriya interaction (2013)
Spin rotation coupling	→	Spin hydrodynamic generation (2015)
Size effect in spin transport	→	Dimensional transition (2009)
⋮		⋮

❖ Newly discovered phenomena

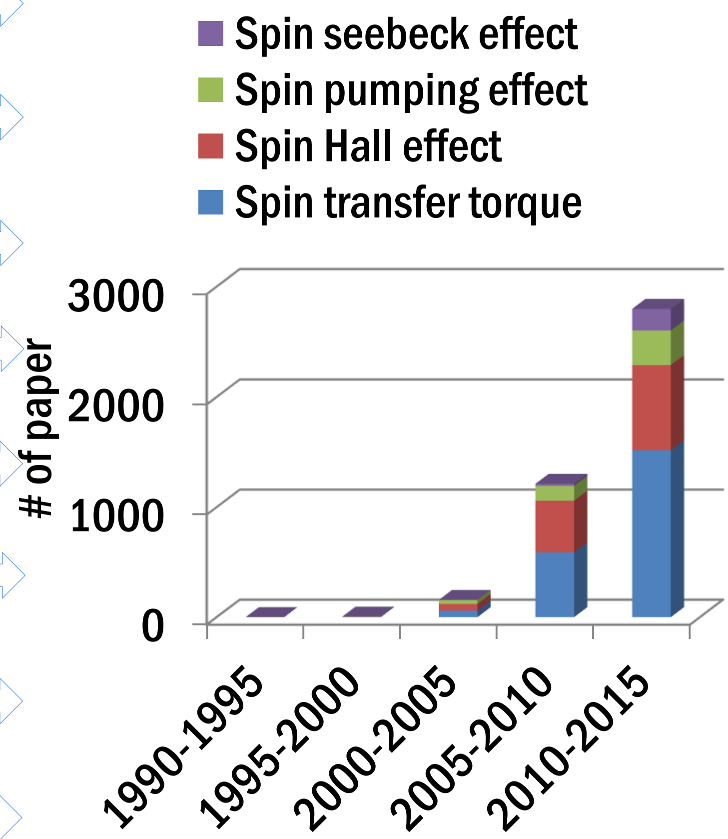
(year) → demonstrated by experimentally

Fundamental mechanism

- Spin dependent scattering
- Spin dependent diffusion
- Spin dependent thermal conductivity
- Spin orbit interaction
- s-d exchange interaction
- Antisymmetric exchange interaction
- Spin rotation coupling
- Size effect in spin transport

⋮

phenomena



❖ web of science

❖ Outline

Brief introduction

Spintronics

Spin dynamics (domain wall dynamics)

By magnetic field
By spin transfer toque
By spin orbit torque

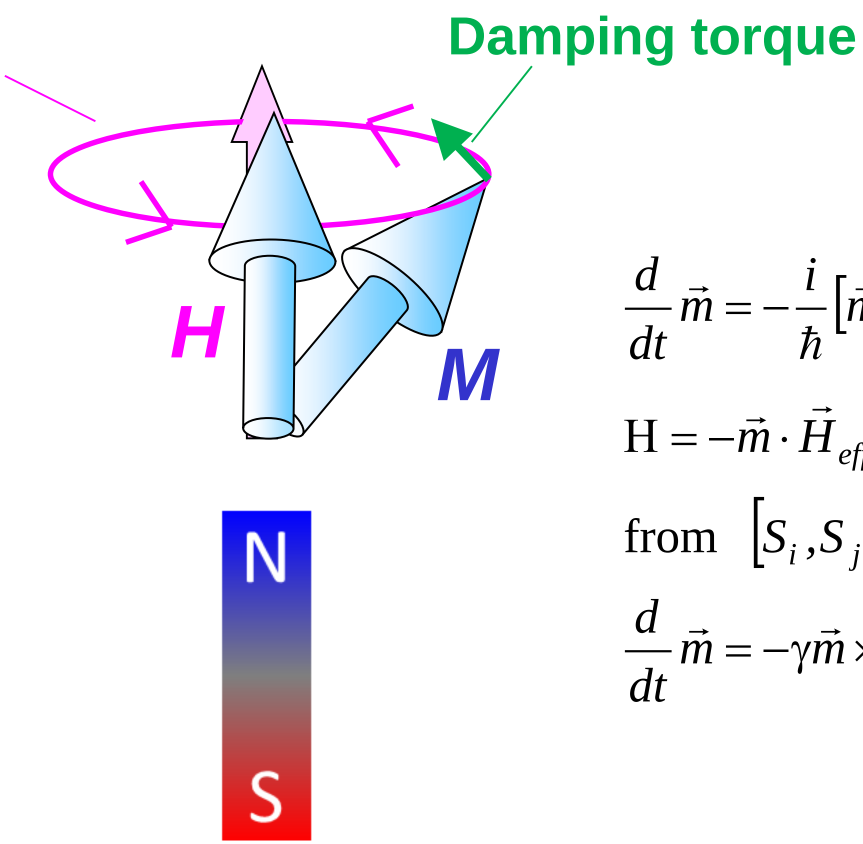
Some spin dynamics phenomena

Ferrimagnetic spin dynamics
Topological spin objects
THz magnon

Summary and Prospect

❖ Spin dynamics induced by magnetic field

$$\frac{\partial \mathbf{M}}{\partial t} = -|\gamma| \mathbf{M} \times \mathbf{H}_{eff} + \frac{\alpha}{M_S} \mathbf{M} \times \frac{\partial \mathbf{M}}{\partial t}$$



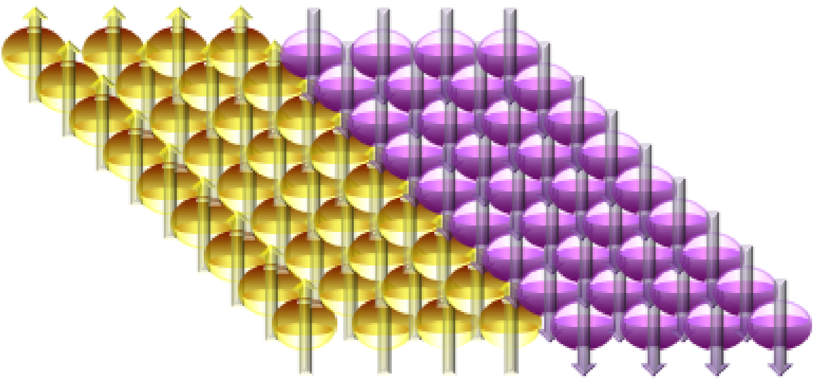
$$\frac{d}{dt}\vec{m} = -\frac{i}{\hbar}[\vec{m}, \mathrm{H}]$$

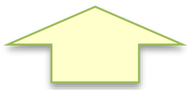
$$\mathrm{H} = -\vec{m} \cdot \vec{H}_{eff}, \quad \vec{H}_{eff} = -\frac{\delta E(m)}{\delta m}, \quad \vec{m} = \gamma \vec{S}$$

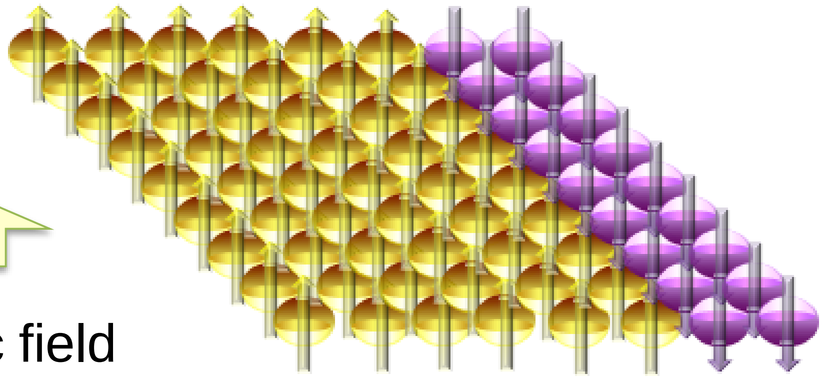
from $[S_i, S_j] = i\hbar S_k$

$$\frac{d}{dt}\vec{m} = -\gamma \vec{m} \times \vec{H}_{eff}$$

❖ Domain wall dynamics induced by magnetic field

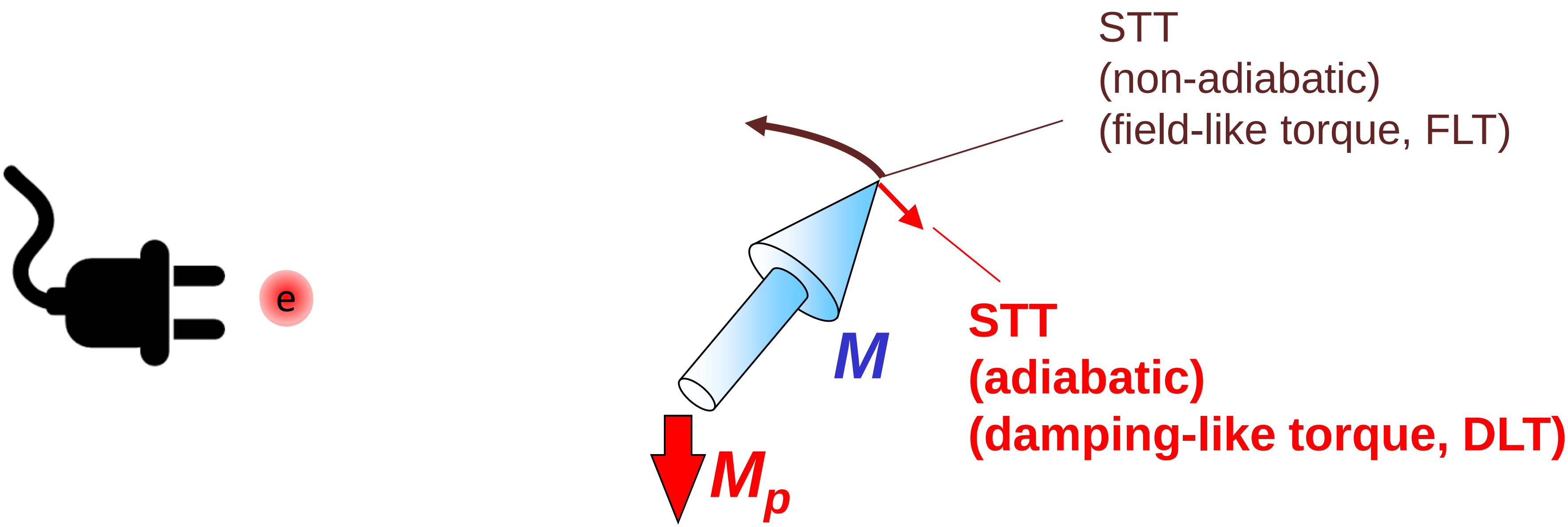






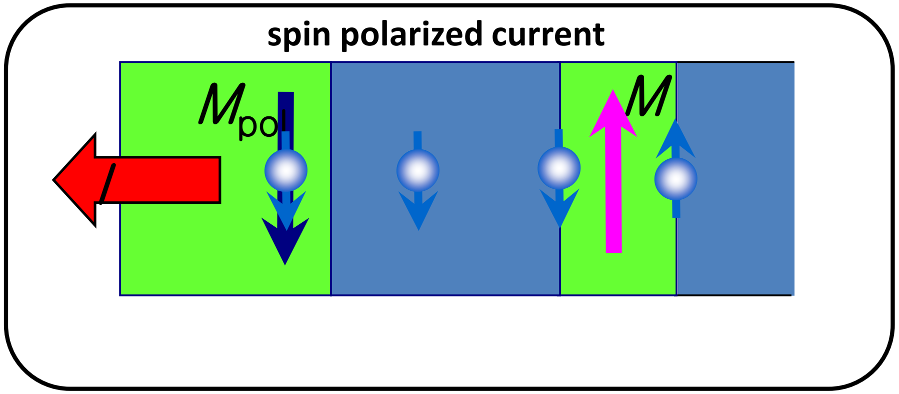
❖ Spin dynamics induced by spin transfer torque

$$\frac{\partial \mathbf{M}}{\partial t} = -|\gamma| \mathbf{M} \times \mathbf{H}_{eff} + \frac{\alpha}{M_S} \mathbf{M} \times \frac{\partial \mathbf{M}}{\partial t} + \frac{b_J}{M_S^2} \mathbf{M} \times \left(\mathbf{M} \times \mathbf{M}_p \right) + \frac{c_J}{M_S} \mathbf{M} \times \mathbf{M}_p$$

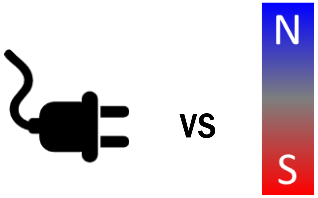


- **Spin torque > Damping torque → Switching**
- **Spin torque ~ Damping torque → Stationary Precession**

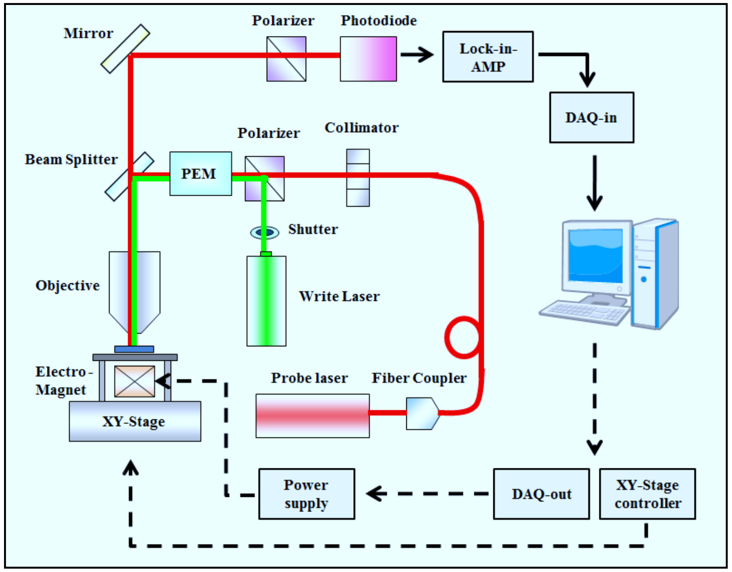
❖ Spin dynamics induced by spin transfer torque

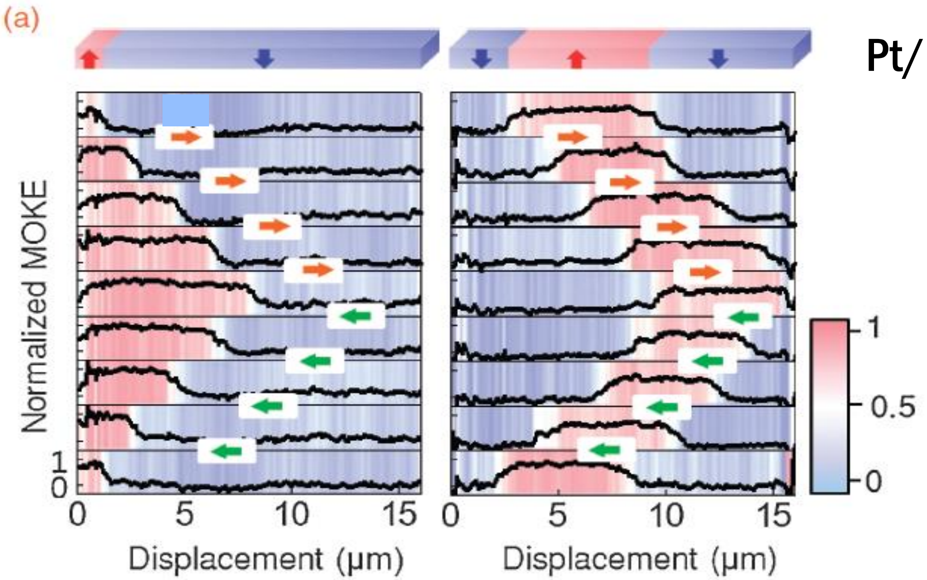


❖ Domain wall dynamics induced by spin transfer torque



Scanning MOKE



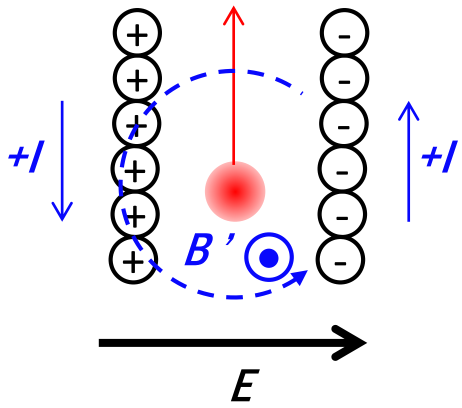


Pt/Co/Pt

KJK *et al. IEEETM (2009)*
KJK *et al. APEX (2010)*
KJK *et al. PRL (2010)*

❖ Spin dynamics induced by spin orbit torque

Moving electron under electric field feels effective magnetic field!

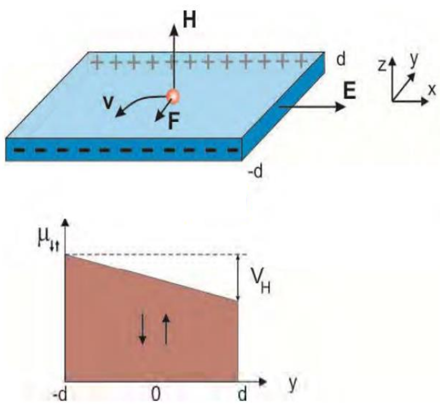


$$H \propto \vec{s} \cdot \left(\vec{p} \times \nabla \phi(\vec{r}) \right)$$

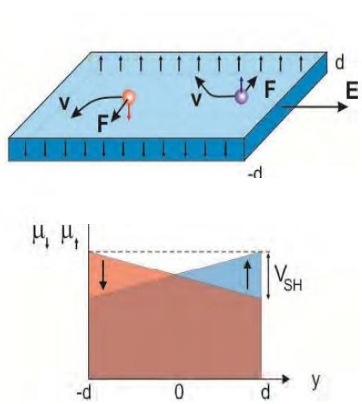
H_{eff}

❖ Spin dynamics induced by spin orbit torque

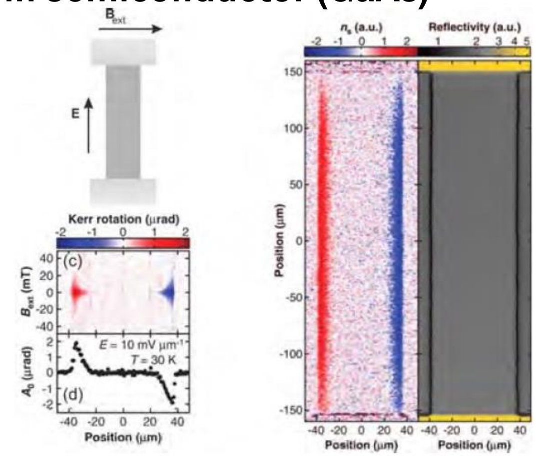
Hall effect



Spin Hall effect



First observation of spin Hall effect in semiconductor (GaAs)



Kato et al. Science (2004)

Charge current (Jc) is converted to spin current (Js)

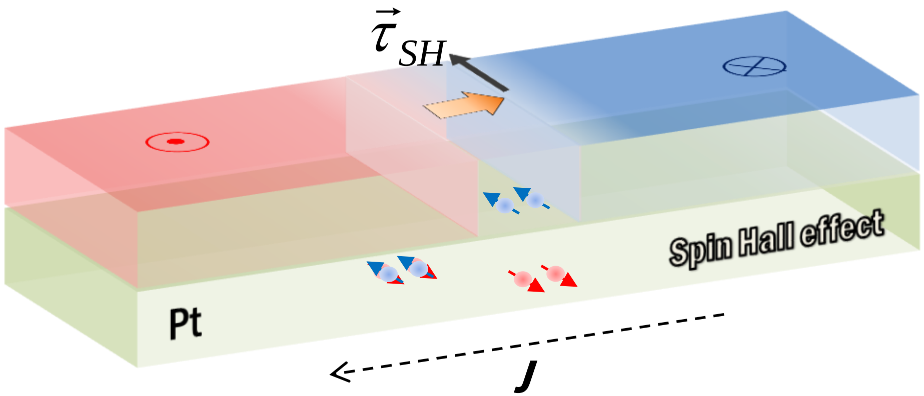
$$\frac{J_S}{J_C} = \theta_{SH} \frac{\hbar/2}{-e}$$

θ_{SH} **: Spin Hall angle**

	Metal (Al)		Metal (Pt,W,Ta)
θ_{SH}	10^{-4}	x1000 →	~10^{-1}

❖ Domain wall dynamics induced by spin orbit torque

Spin current injection by spin Hall effect



$$\frac{\partial \mathrm{M}}{\partial t} = -|\gamma| \mathrm{M} \times \mathrm{H}_{eff} + \frac{\alpha}{M_S} \mathrm{M} \times \frac{\partial \mathrm{M}}{\partial t} + \frac{\alpha_{SHE}}{M_S} \mathbf{M} \times (\sigma \times \mathbf{M})$$

Spin Hall torque

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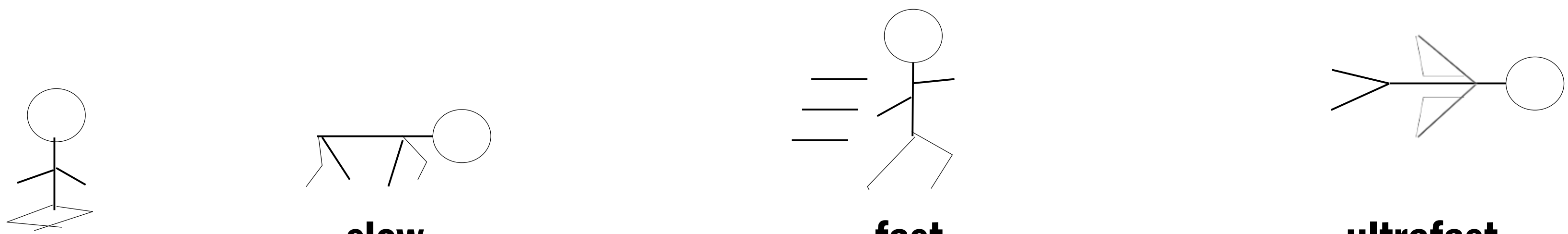
❖ Time scale in spin dynamics

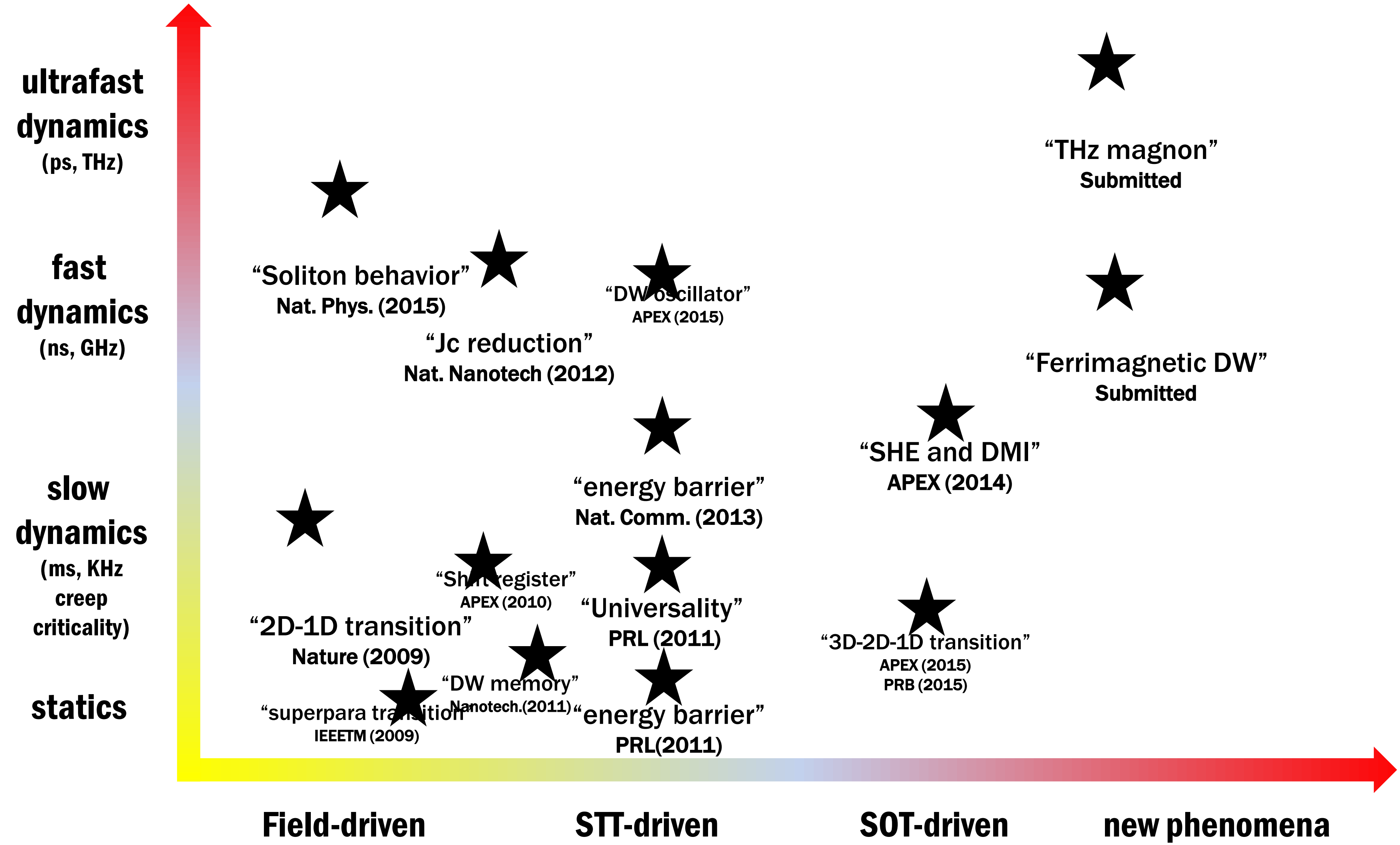


	static	slow dynamics		fast dynamics		ultrafast dynamics
time		1 s	1 ms	1 μs	1 ns	1 ps
frequency		1 Hz	1 KHz	1 MHz	1 GHz	1 THz

phenomena	Thermal Activation	flow Motion	Damping/Precession
	$E_B >> k_B T$	$E_B \sim k_B T$	$E_B \sim 0$

Detection tech. Electrical detection — Optical detection

❖ What I have done so far…



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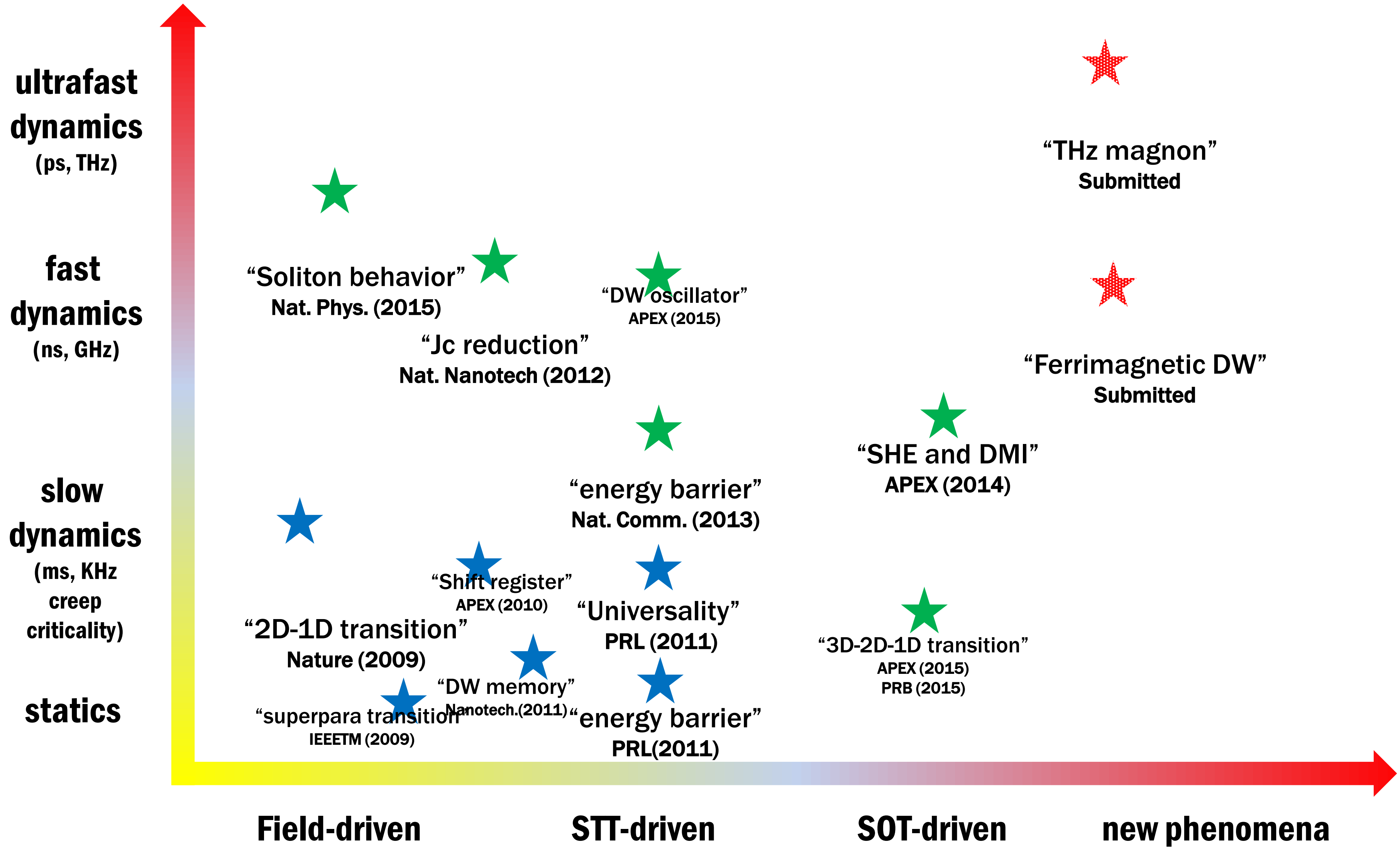

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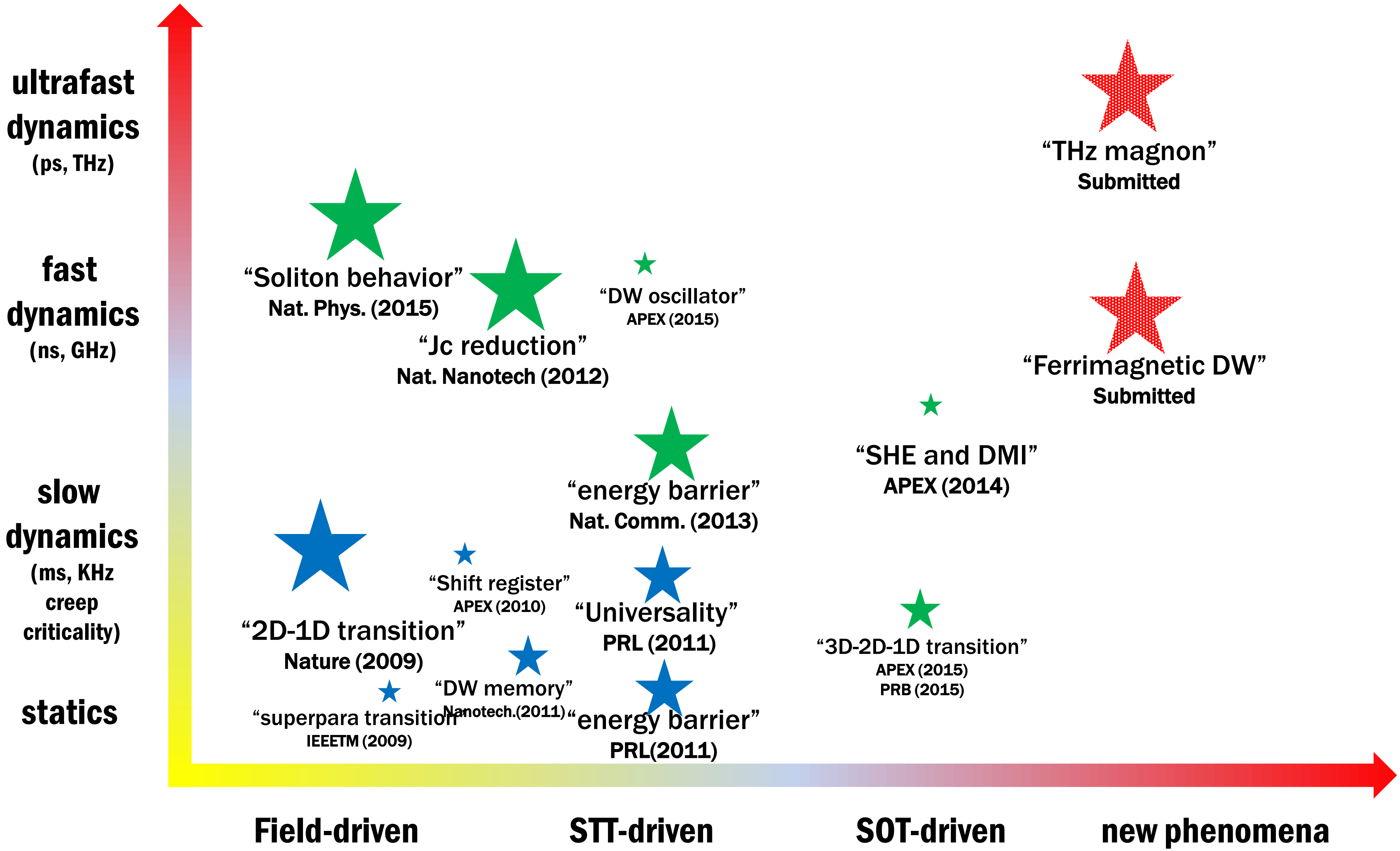
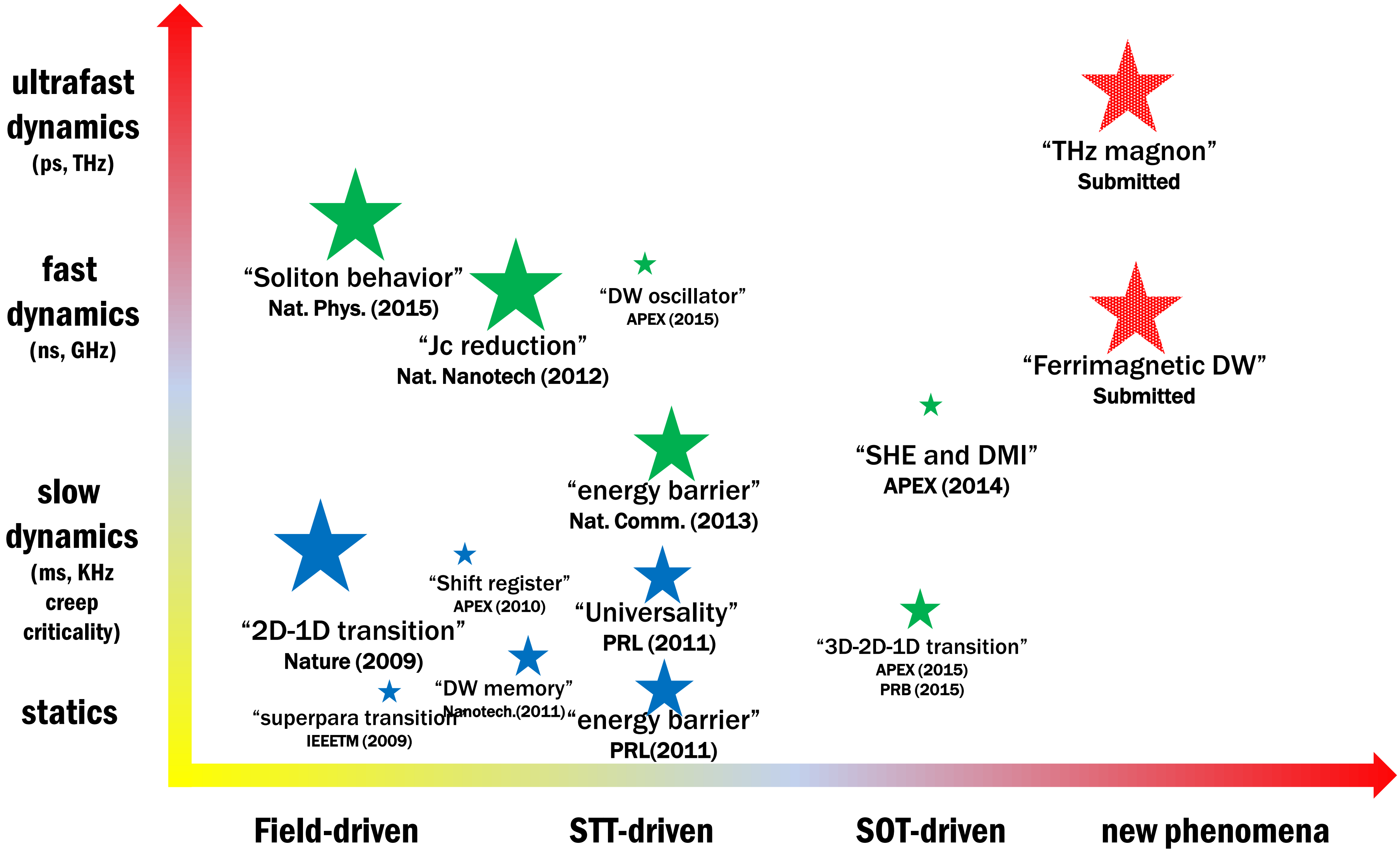
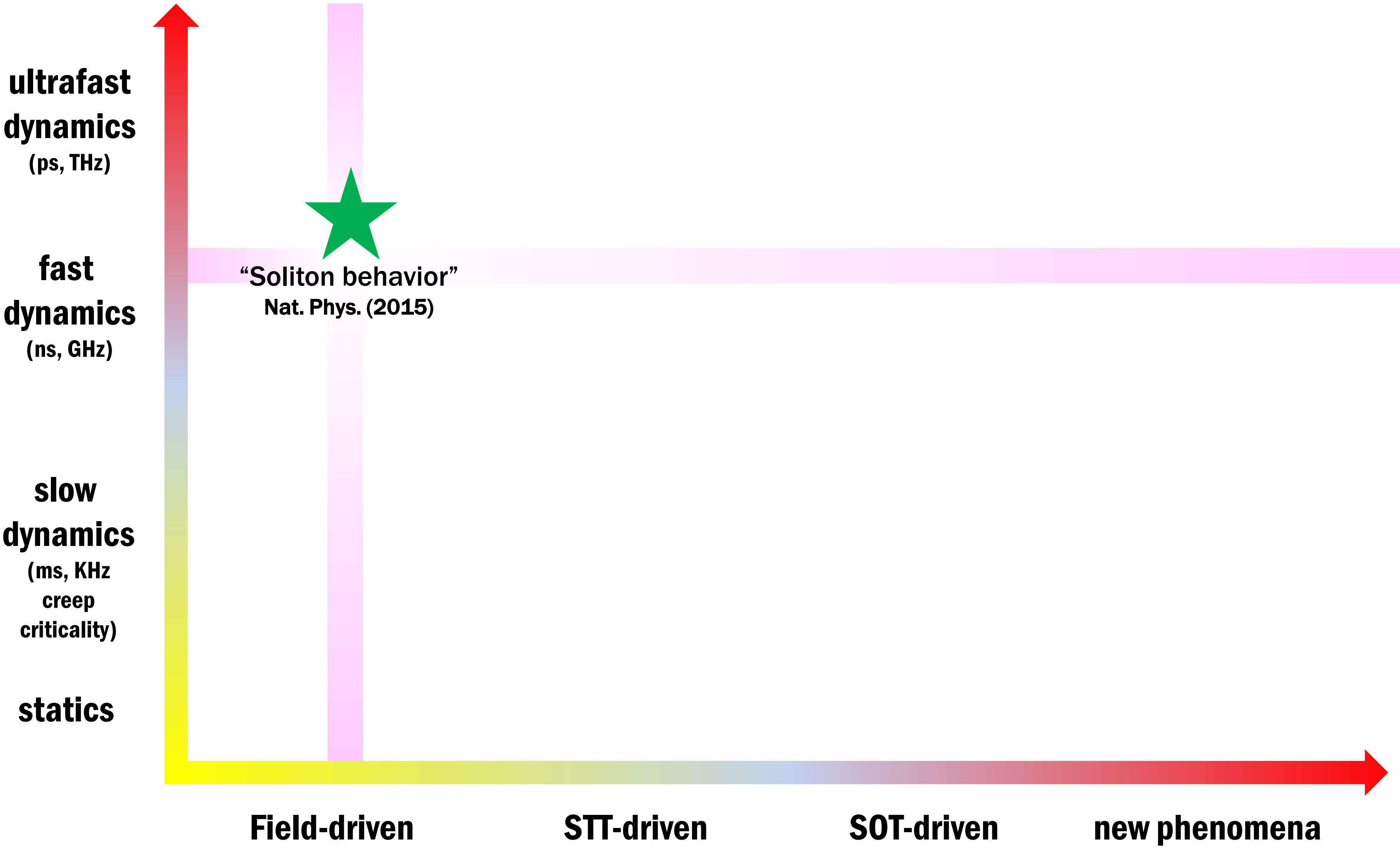


❖ Today's topic is…

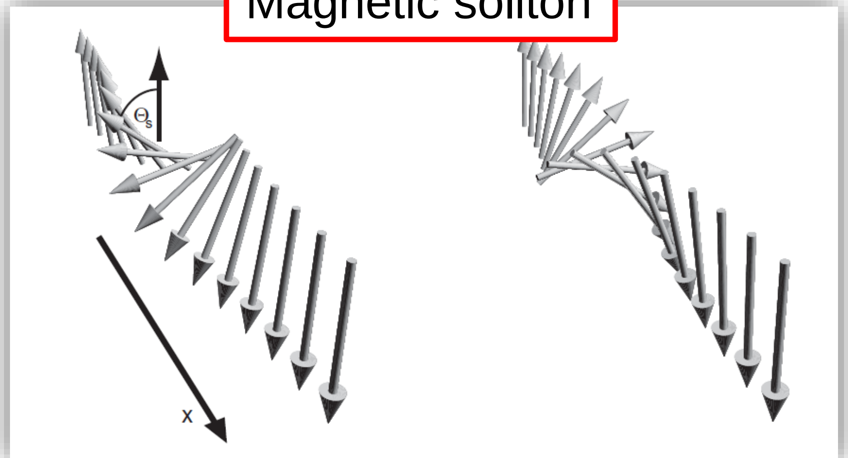


❖ Today's topic is…



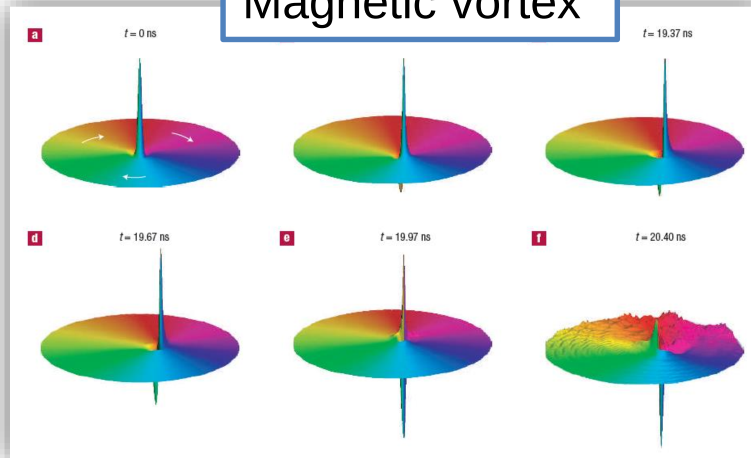
❖ Topological spin objects

Magnetic soliton



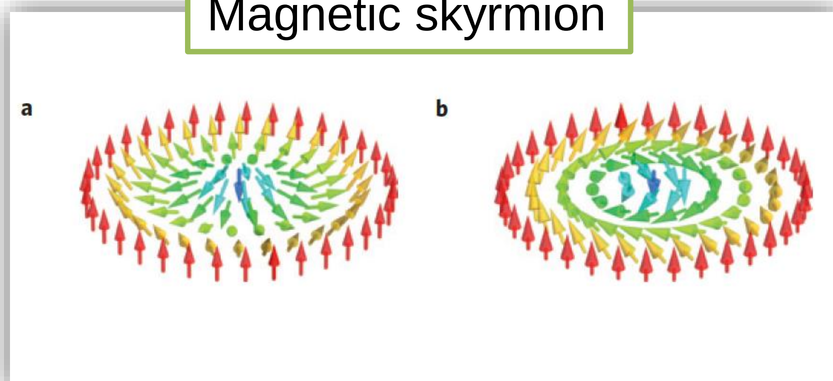
Adv. Phys. 61, 1 (2012)

Magnetic vortex



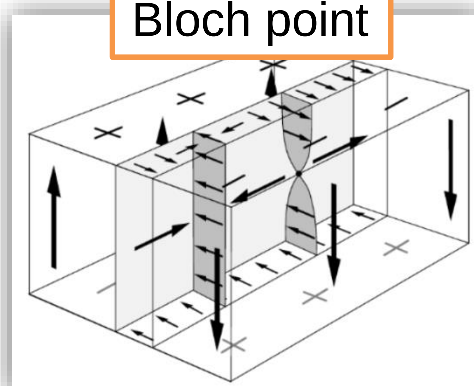
Nat. Mater. 6, 269 (2007)

Magnetic skyrmion



Nat. Nanotechnol.8,152 (2013)

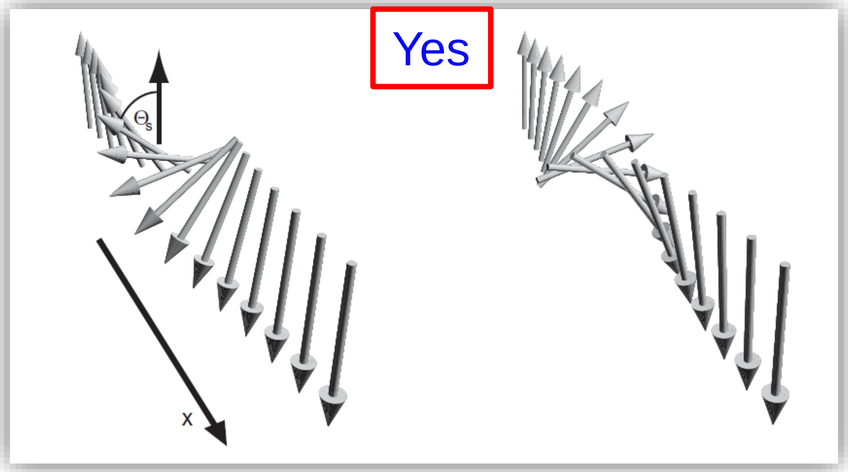
Bloch point



Magnetic domains, Springer

These non-uniform magnetic configurations are protected topologically.
→ Extraordinary stabiltiy → memory devices

❖ Is magnetic domain wall a topological object?



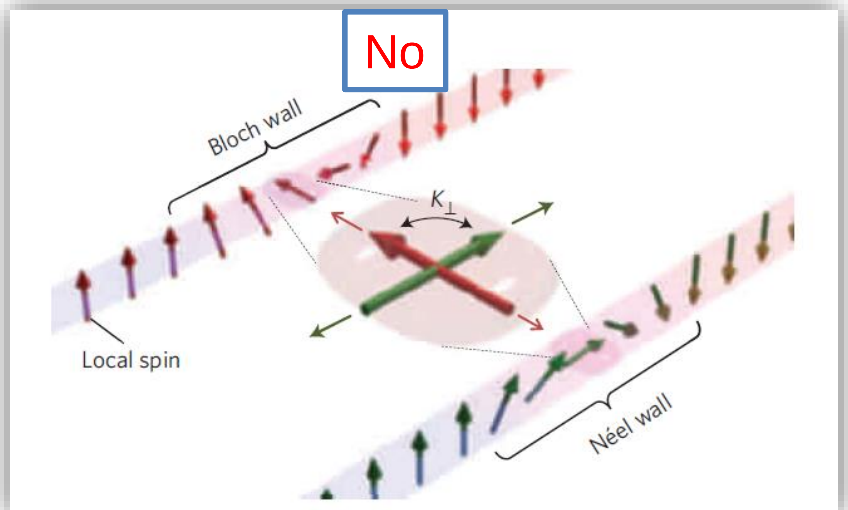
Magnetic soliton

Four-fold degeneracy

Up → Down and Down → Up

x

Left-handed and right-handed helicity

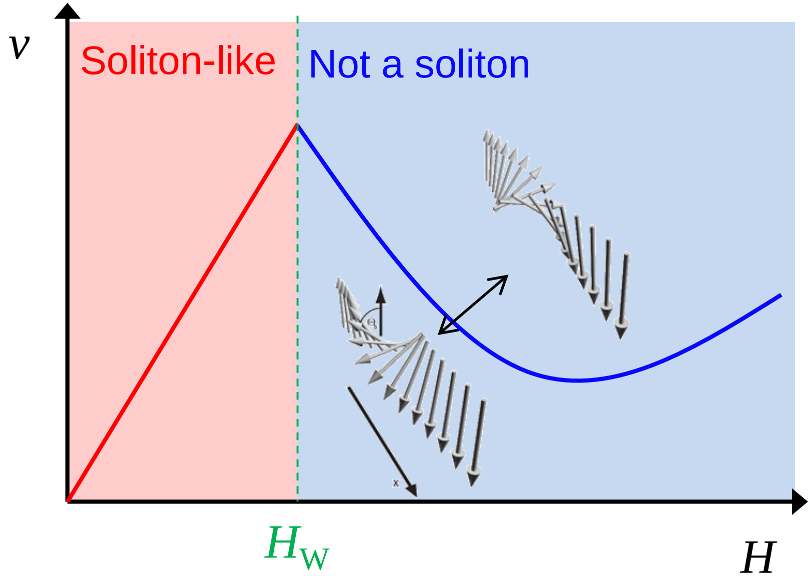


Magnetic domain-wall

If precessional motion occurs,
→ helicity is changed

→ *DW motion is generally not a topologically protected in the presence of a external field because the DW can be deformed by finite energy.*

❖ Magnetic domain wall dynamics in one dimension



Precessional regime

$$v = \gamma\Delta \frac{\alpha}{1+\alpha^2} H$$

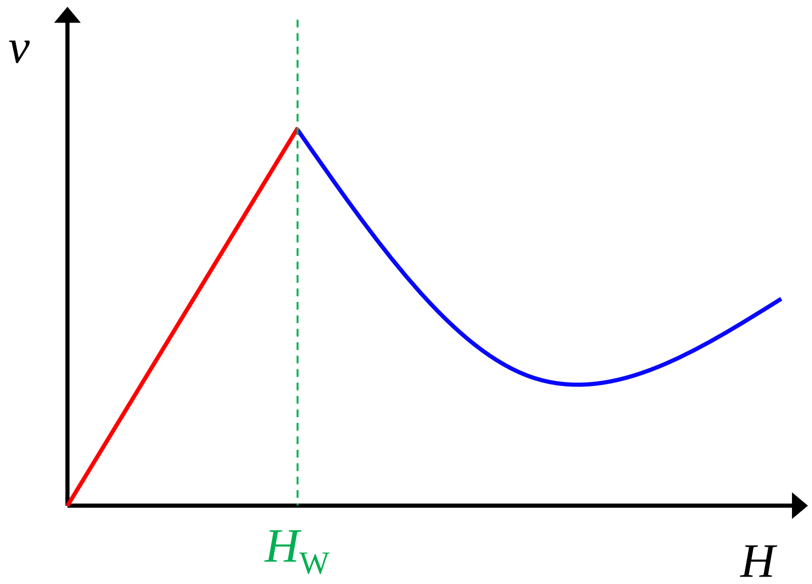
Steady regime

$$v = \frac{\gamma\Delta}{\alpha} H$$

Walker breakdown field

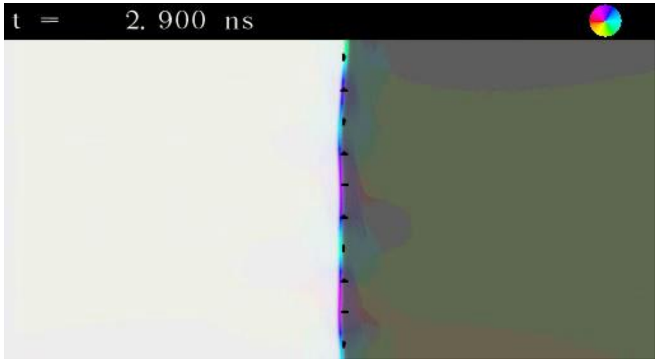
$$H_W = 2\pi\alpha M_S \left| N_y - N_x \right|$$

❖ Magnetic domain wall dynamics in two dimension



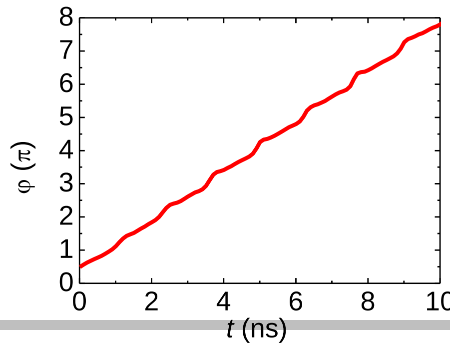
Precessional regime

$$v = \gamma\Delta \frac{\alpha}{1+\alpha^2} H$$



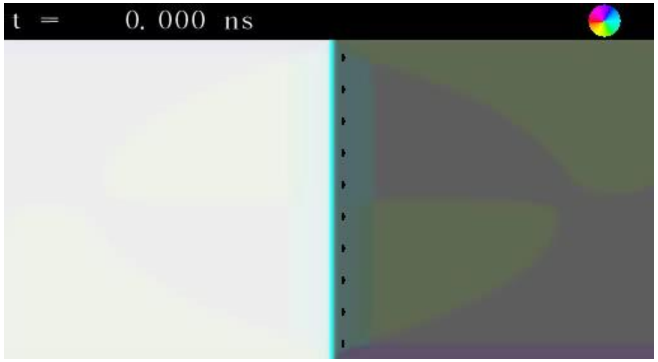
Precession

→ Evolution of vertical Bloch lines



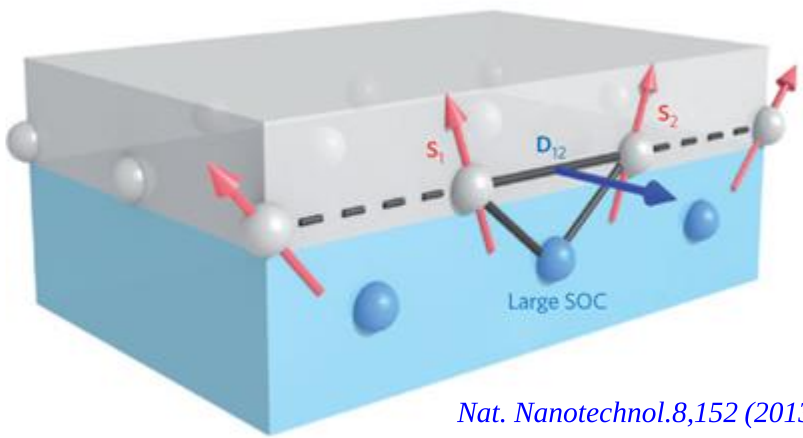
Steady regime

$$v = \frac{\gamma\Delta}{\alpha} H$$



Very complicate.
But in analogous to precessional motion

❖ Interfacial Dzyaloshinskii–Moriya interaction (DMI)



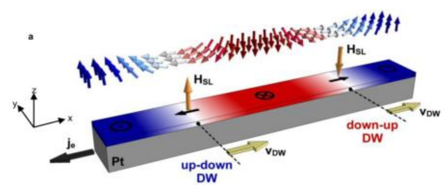
Nat. Nanotechnol.8,152 (2013)

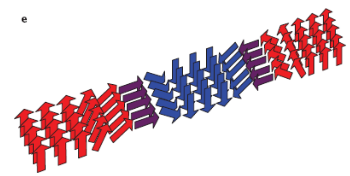
- Second order exchange interaction

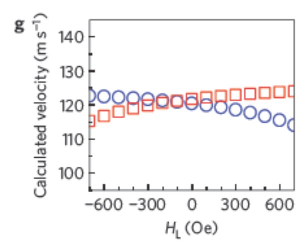
  $\boldsymbol{H}_{\mathrm{DMI}} = -\boldsymbol{D}_{12} \bullet (\boldsymbol{S}_1 \times \boldsymbol{S}_2)$,

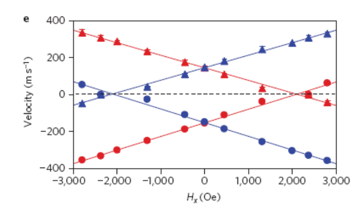
- Emerges at the interface
  (broken inversion symmetry)

- Prefers chiral spin structure





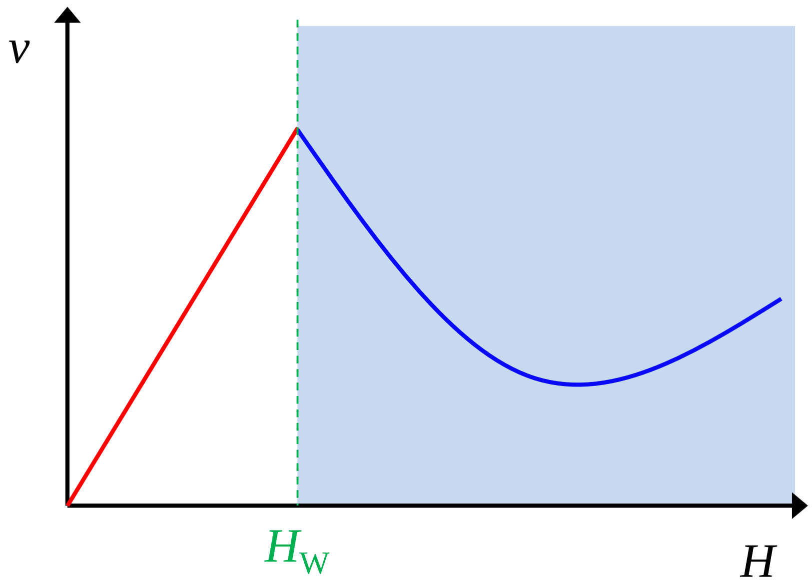


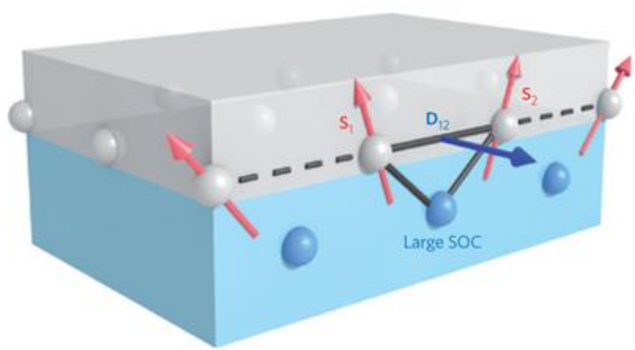


S. Emori, *et al.*,*Nat. Mater*. (2013)

K. S. Ryu *et al.*, *Nat. Nanotech*. (2013)

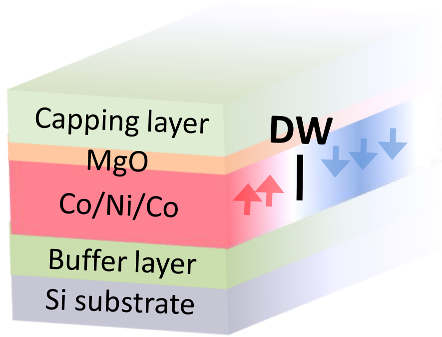
❖ Magnetic domain wall dynamics under DMI





❖ Two controlled samples

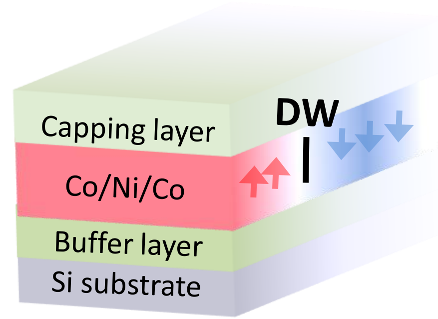
[asymmetric structure]



large DMI

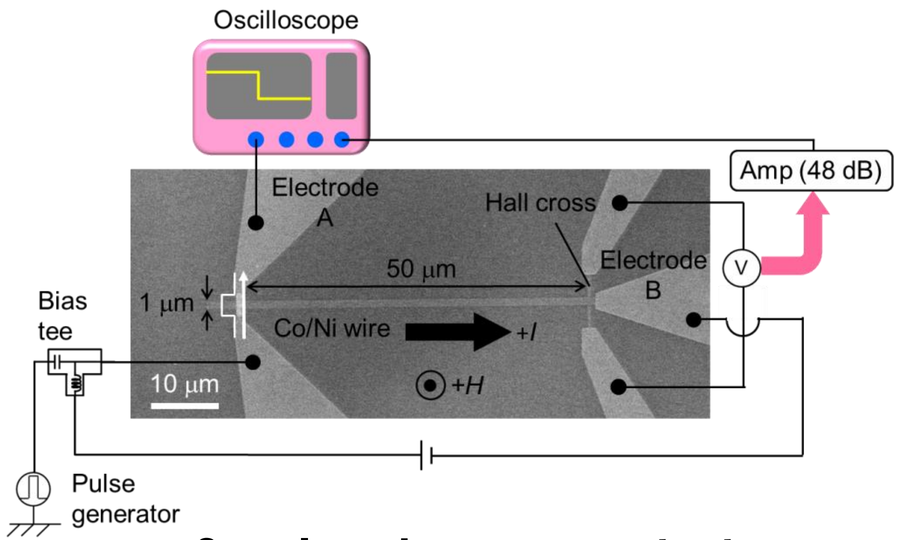
[Ta(4)/Pt(2)/MgO(1)/Co(0.3)/Ni(0.6)/Co(0.3)/Pt(2)/Ta(4)/ Si sub. (unit: nm)]

[symmetric structure]



No DMI

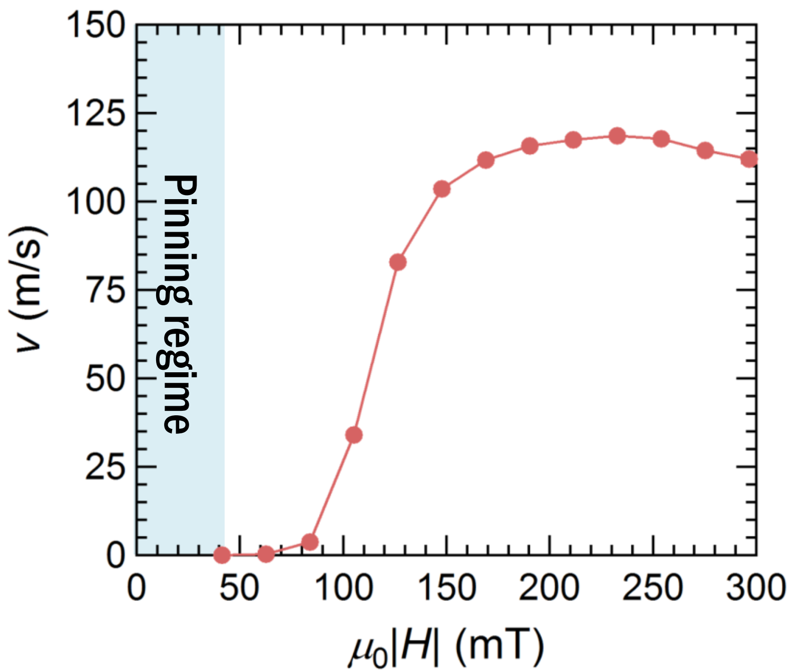
[Ta(4)/Pt(2)/Co(0.3)/Ni(0.6)/Co(0.3)/Pt(2)/Ta(4)/ Si sub. (unit: nm)]



Sample and measurement setup

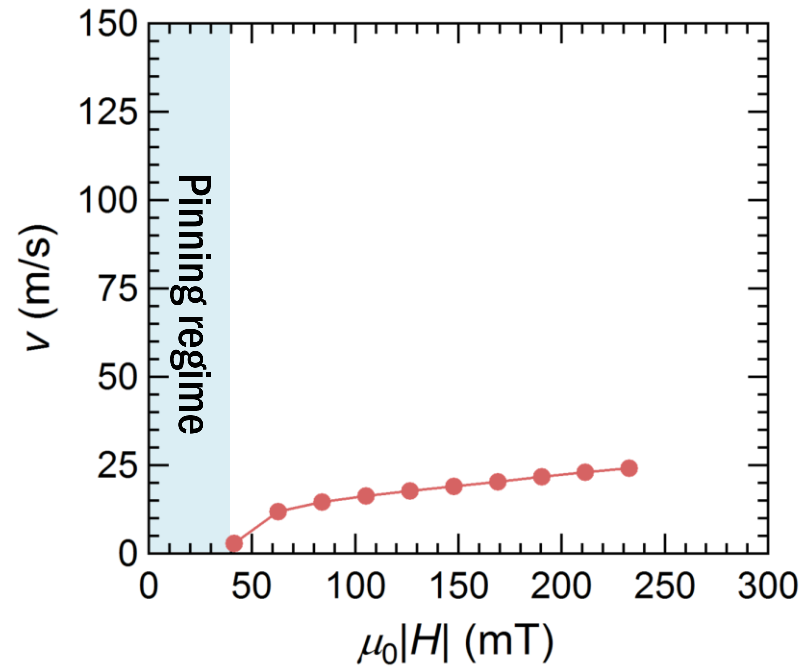
❖ Experimental results

[asymmetric structure] **large DMI**



Fast DW velocity.
v saturates in a wide range of *H*.

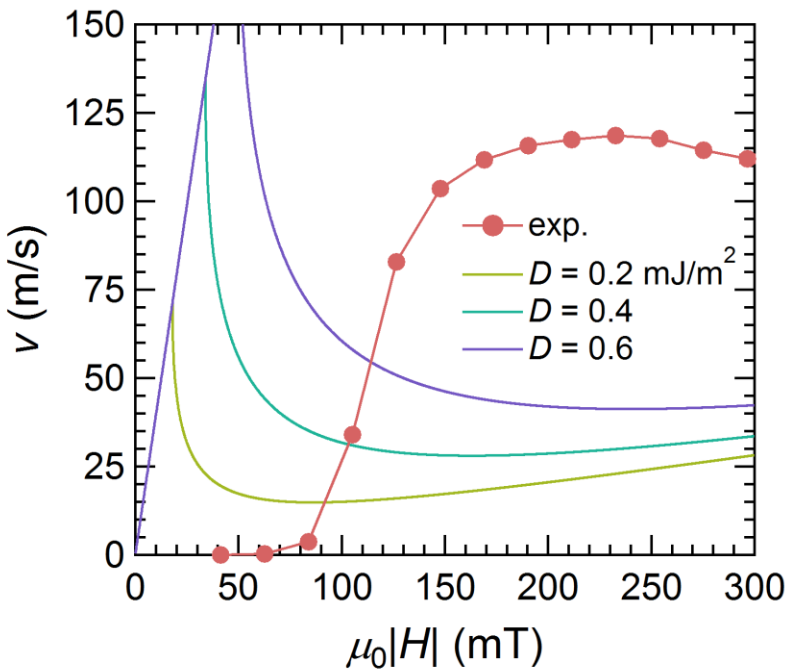
[symmetric structure] **No DMI**



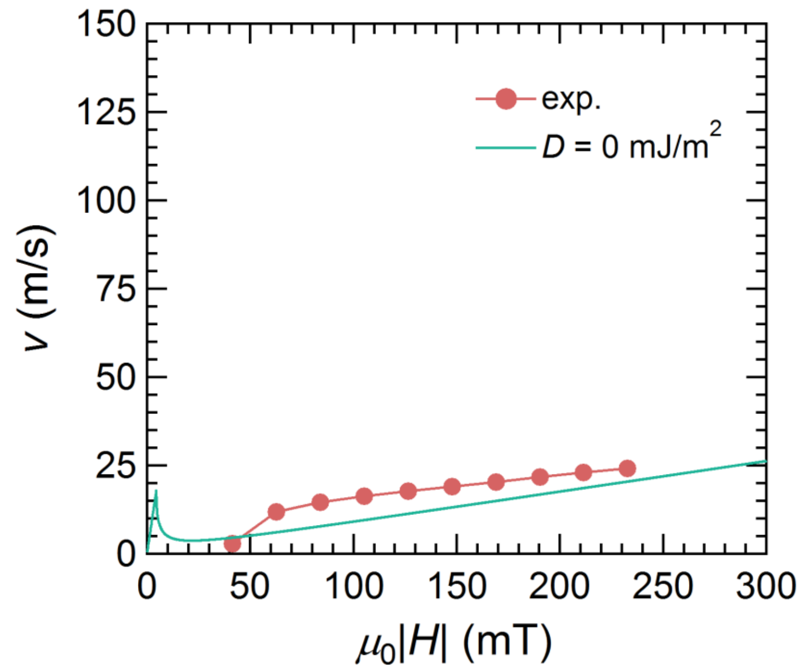
Slow DW velocity.
v gradually increases with *H*.

❖ Compare to the theory

[asymmetric structure] **large DMI**



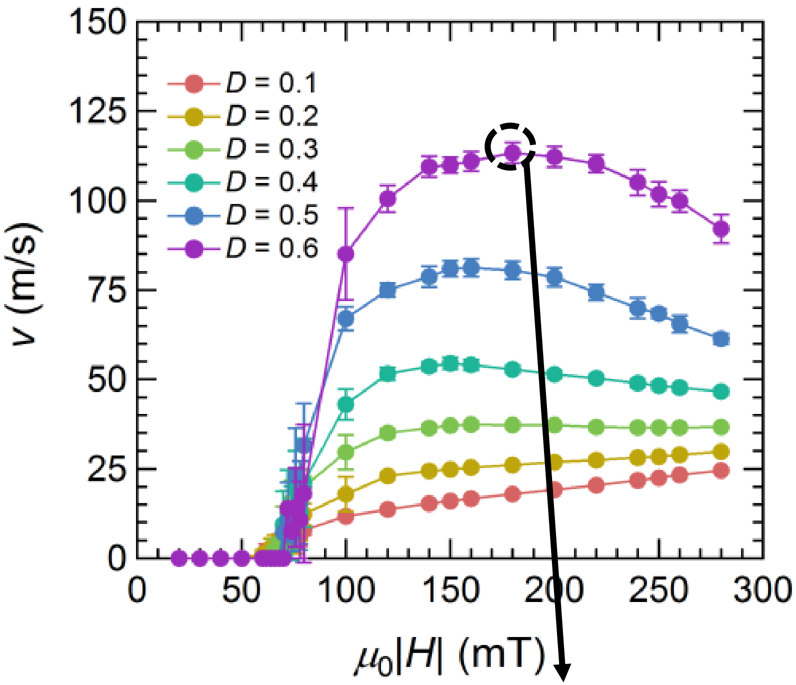
[symmetric structure] **No DMI**



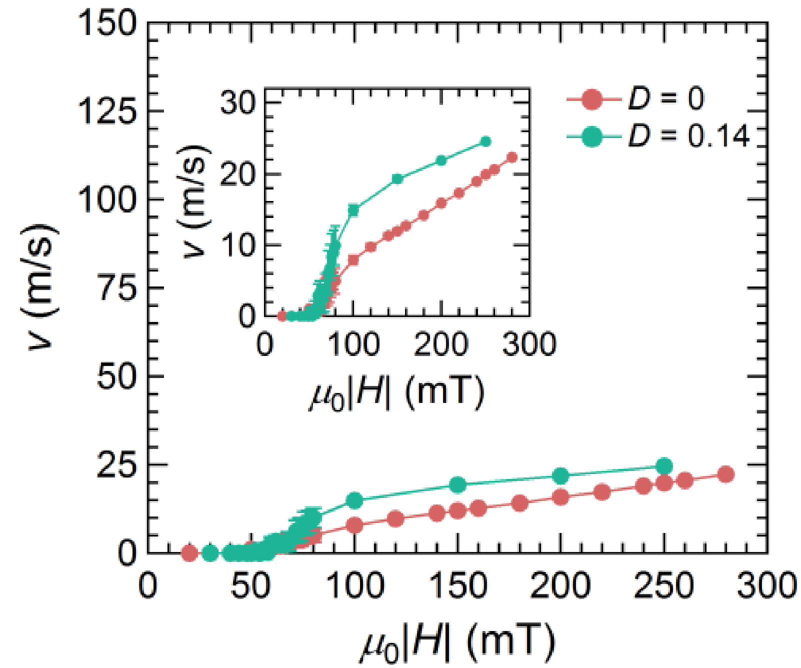
- Theoretical model cannot explain the experimental results.
- DMI enhances the DW velocity in the precessional regime!

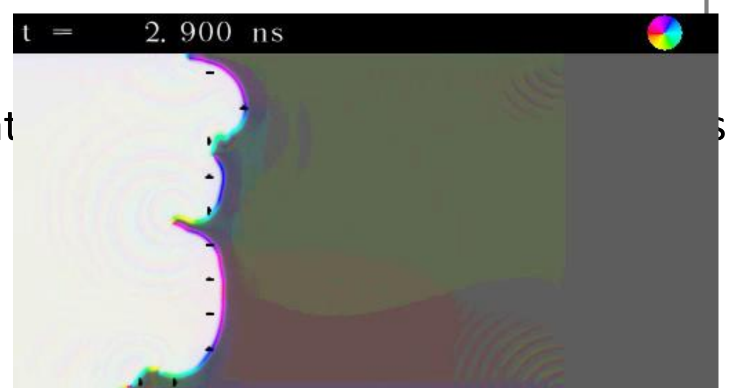
❖ Compare to the simulation

[asymmetric structure] **large DMI**



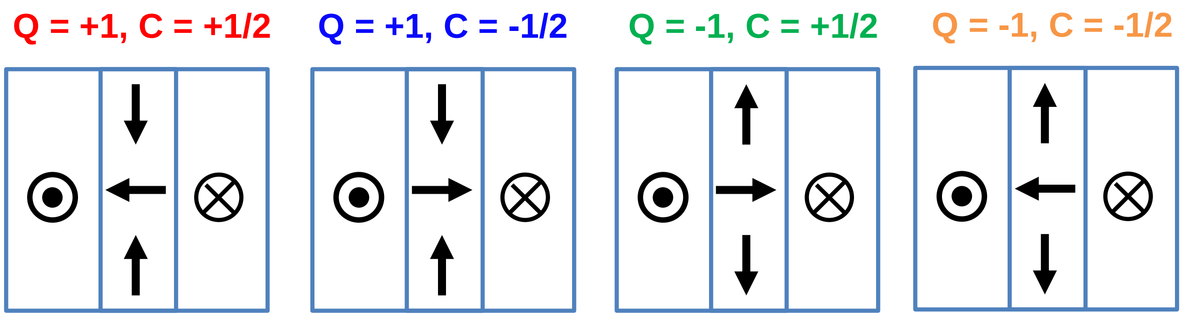
[symmetric structure] **No DMI**



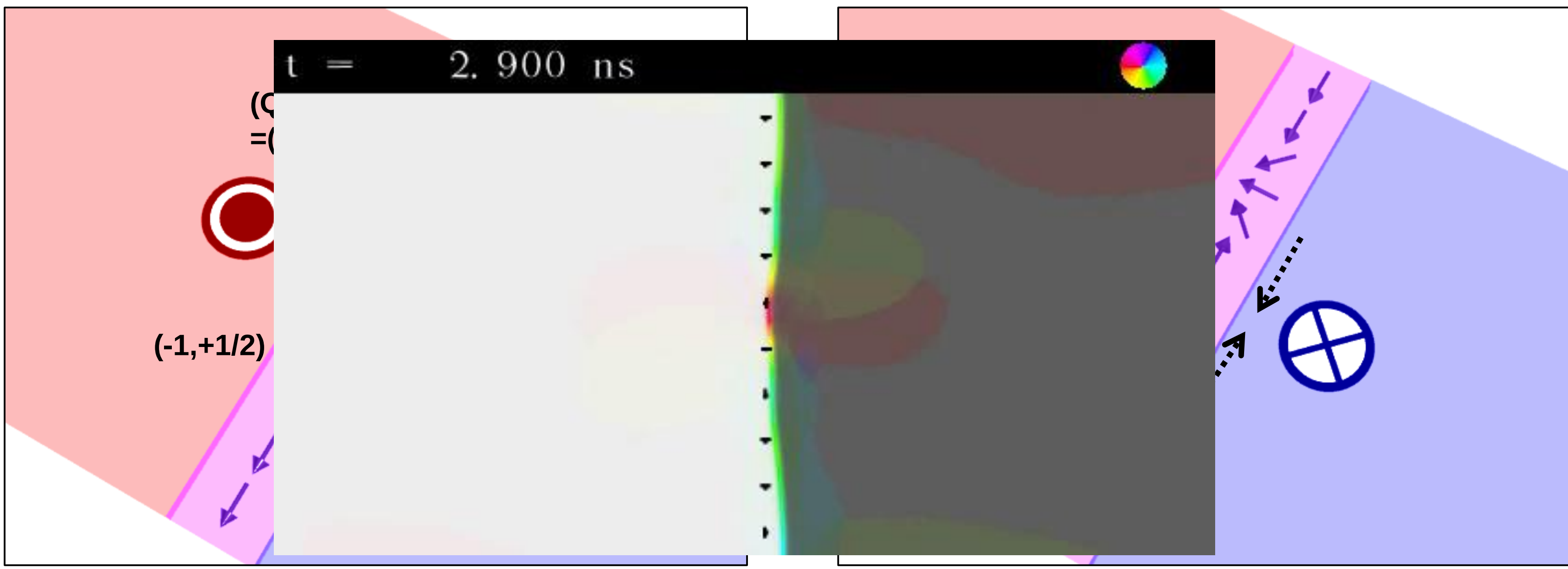


Simulat … sults very well!

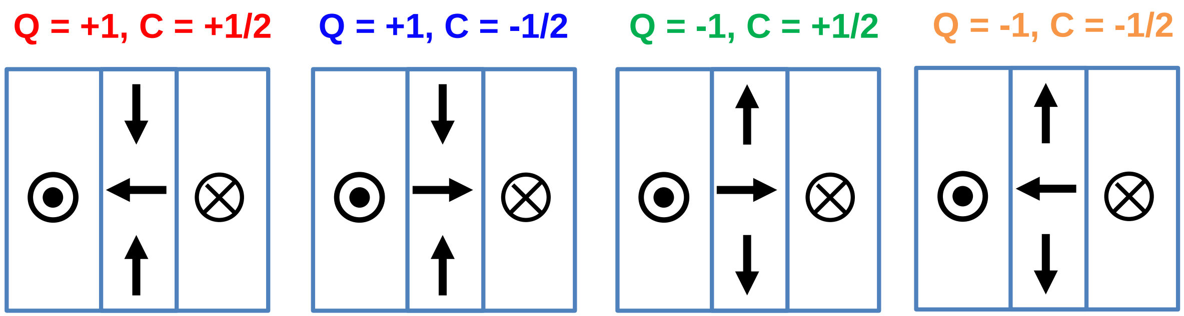
❖ Topological characteristics of vertical Bloch lines (VBLs)



Four-fold degeneracy
Charge Q x chirality C



❖ Topological characteristics of vertical Bloch lines (VBLs)



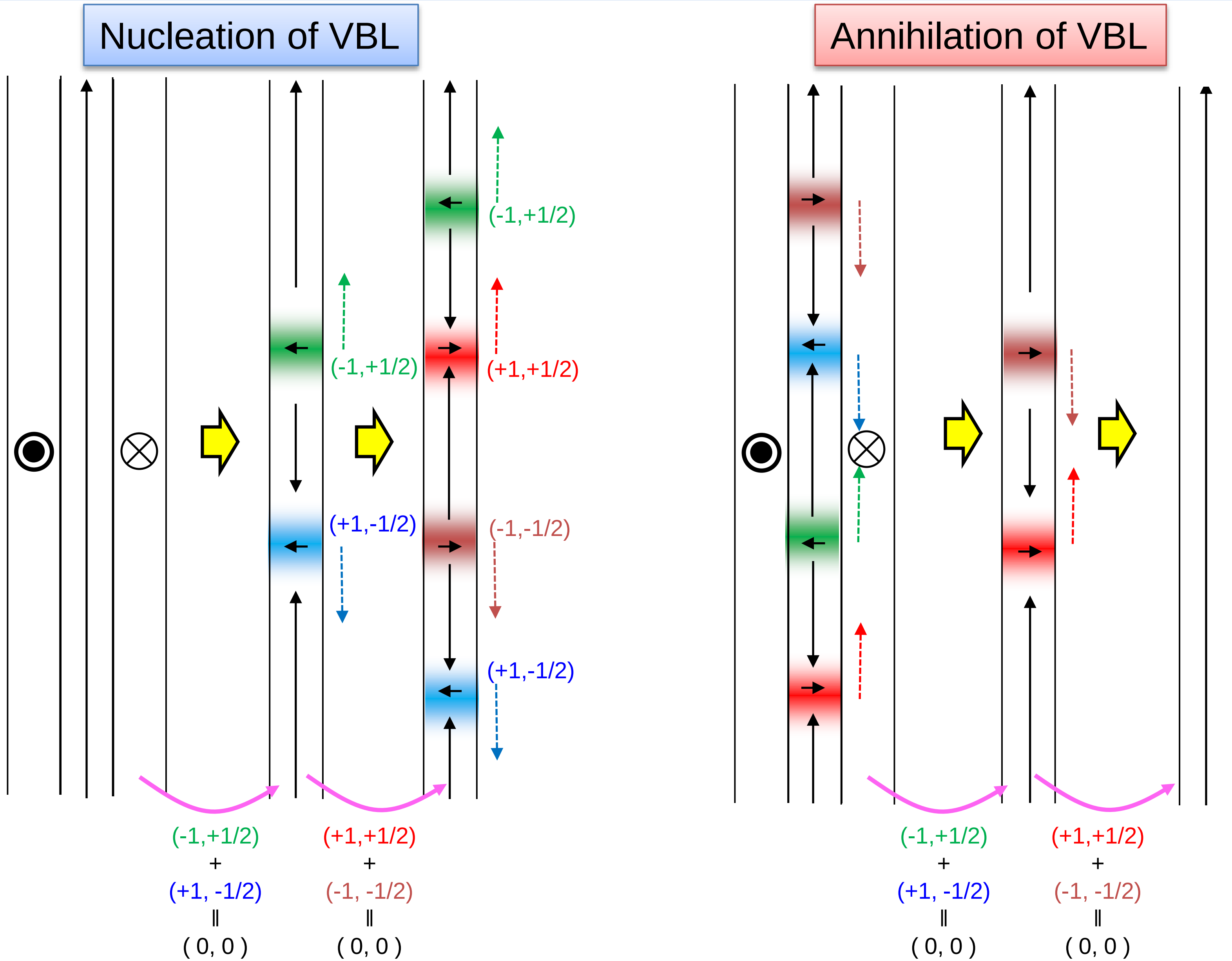
Four-fold degeneracy
Charge Q x chirality C

$\sum_i Q_i$ *Total charge* ⇒ *Topological charge of DW*

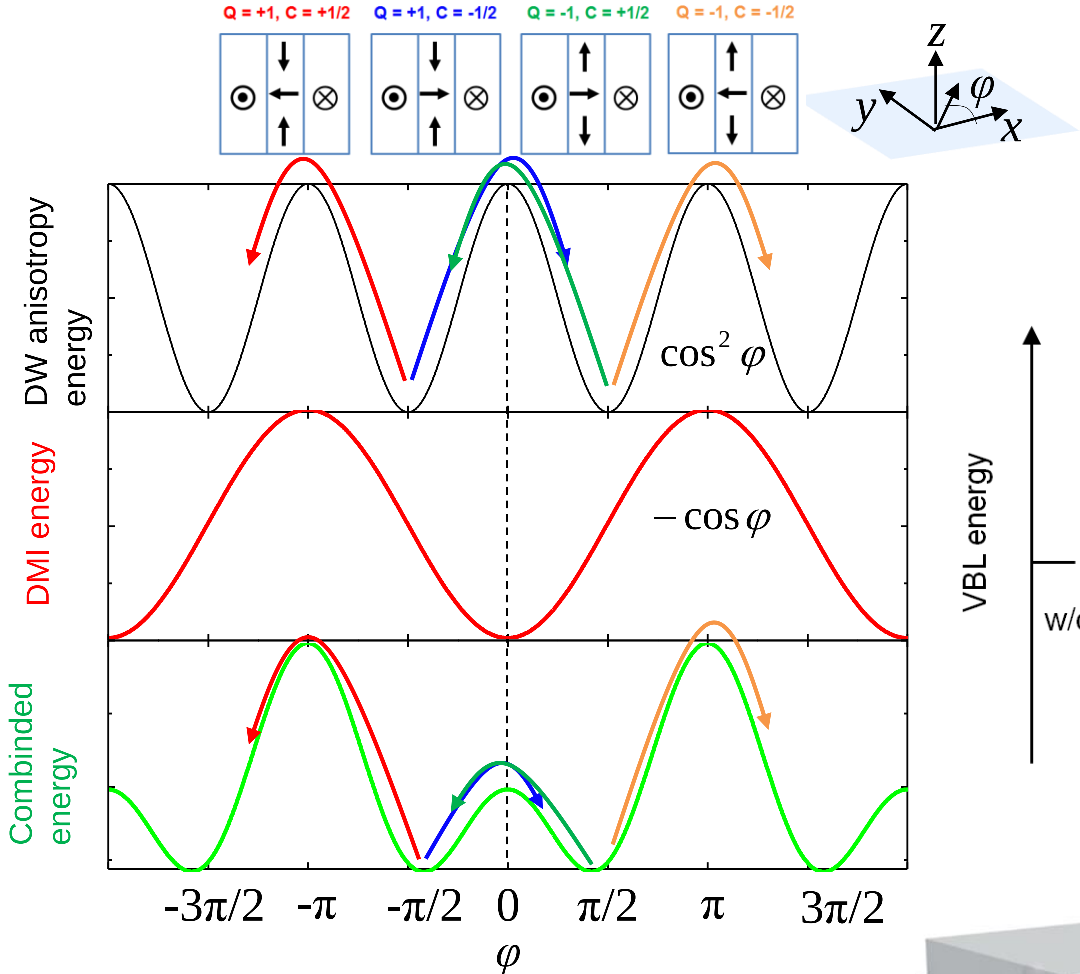
$\sum_i C_i$ *Total chiraltiy* ⇒ *Topological winding number of DW*

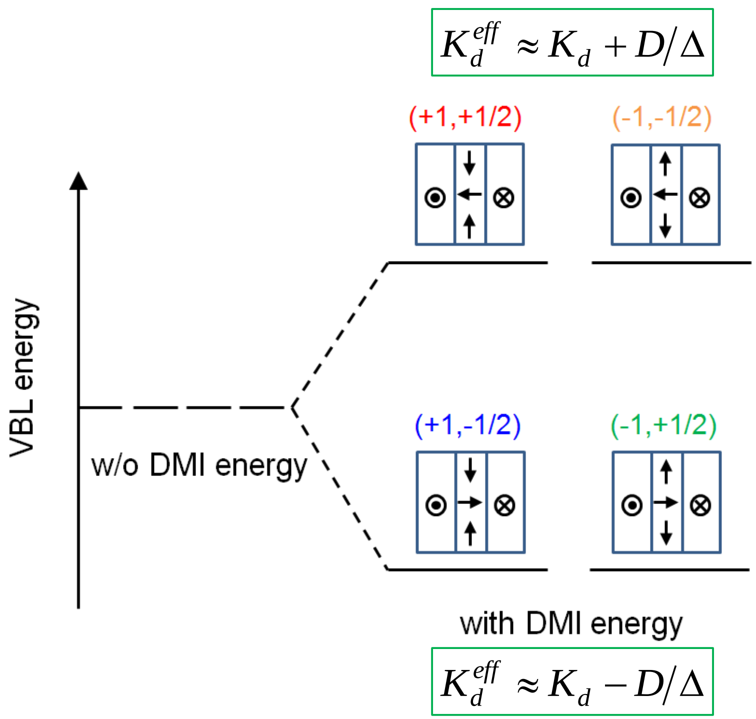
⇒ Topological constraint

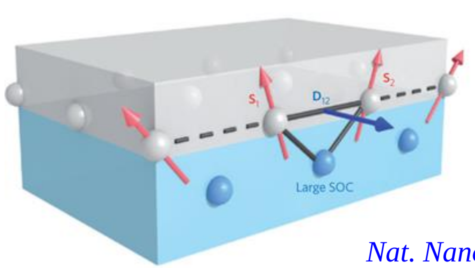
❖ Topological characteristics of vertical Bloch lines (VBLs)



❖ Topological characteristics of VBL under DMI

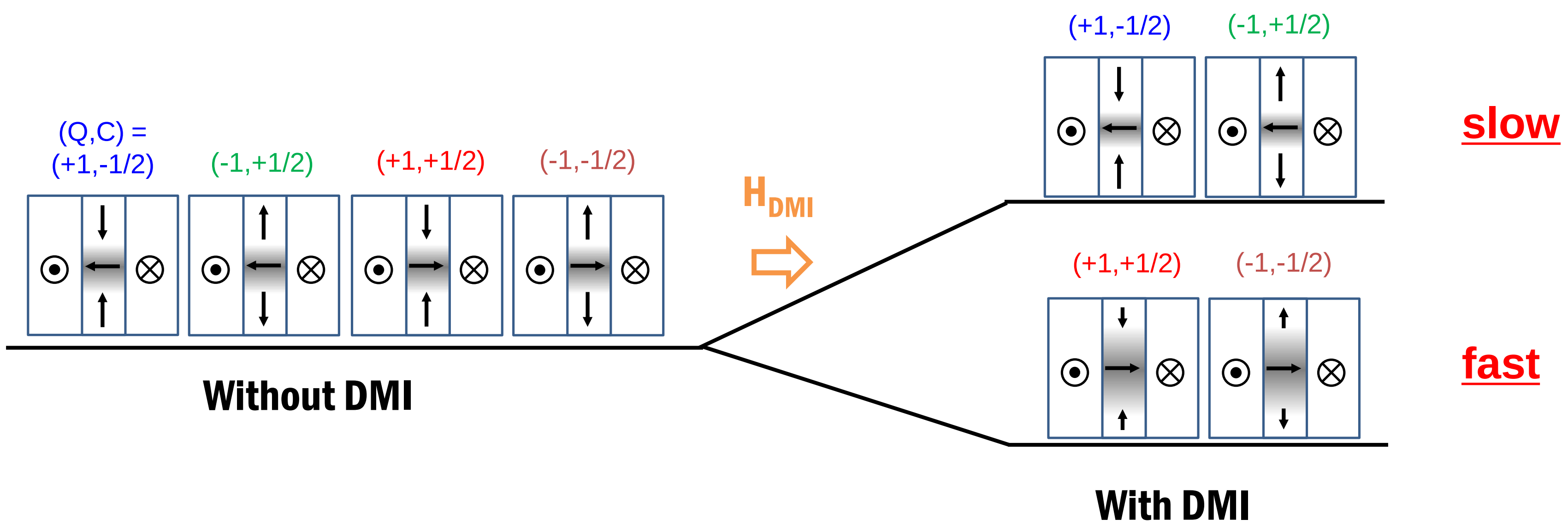






Nat. Nanotechnol.8,152 (2013)

❖ Topological characteristics of VBL under DMI



Total energy

$$K_d^{eff} \approx K_d \pm D/\Delta$$

VBL width

$$\Lambda_{e,g} = \sqrt{\frac{A}{K_d^{eff}}} = \sqrt{\frac{A}{K_d \pm D/\Delta}}$$

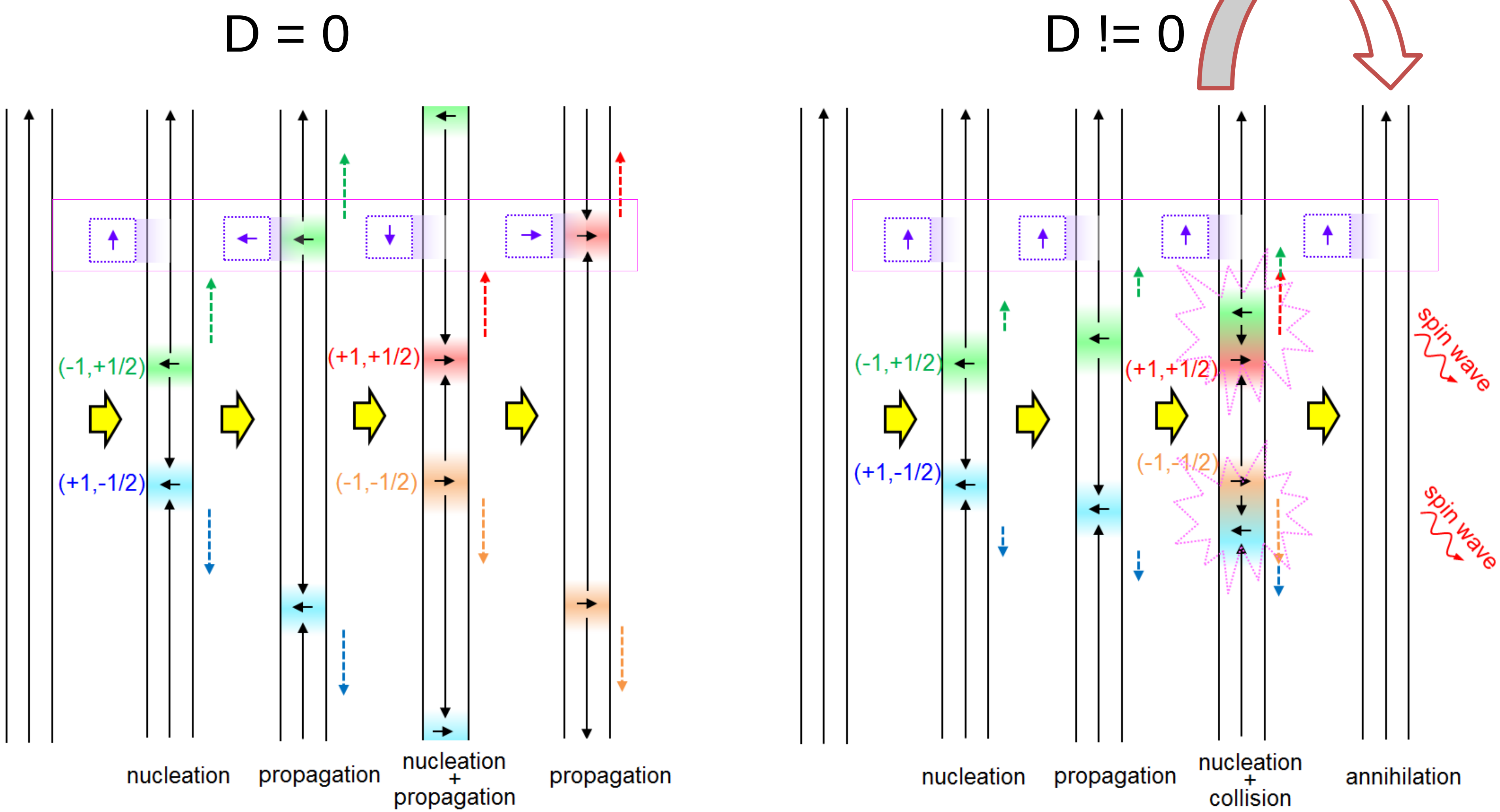
VBL velocity

$$v_{e,g} = -\frac{\pi\gamma\Lambda_{e,g} H}{2\alpha^2}$$

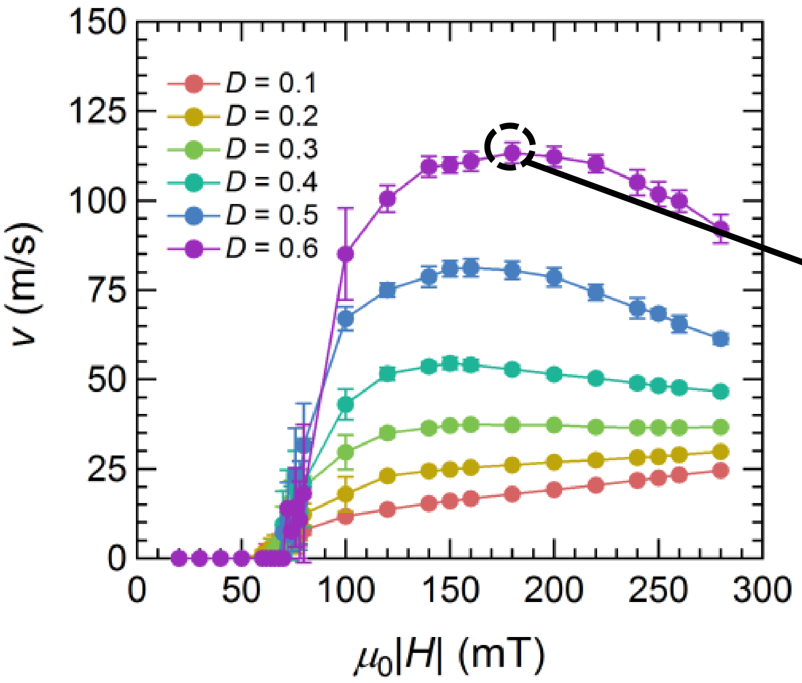
Energy splitting generates velocity difference

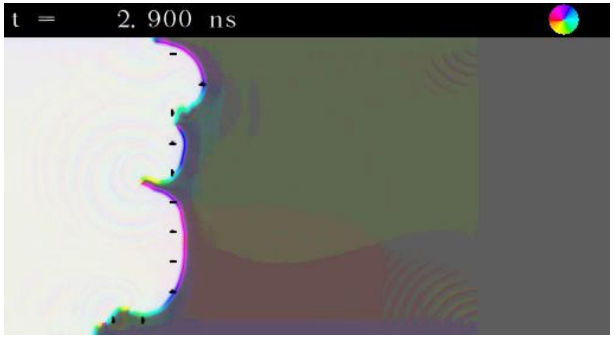
❖ Unidirectional collision of VBLs

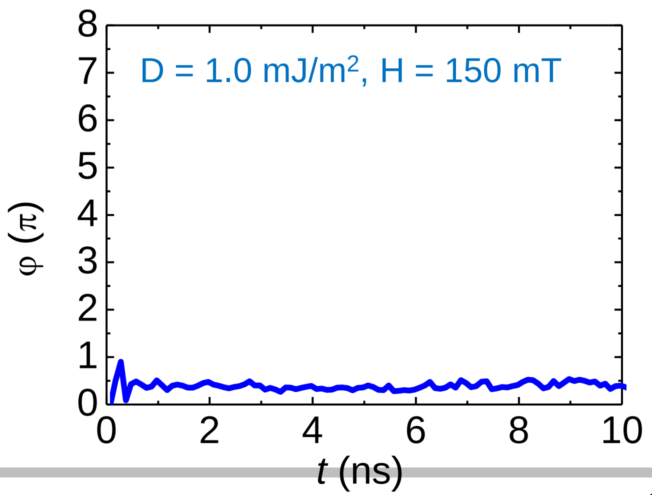
Topological winding number changes
→ Energy dissipation



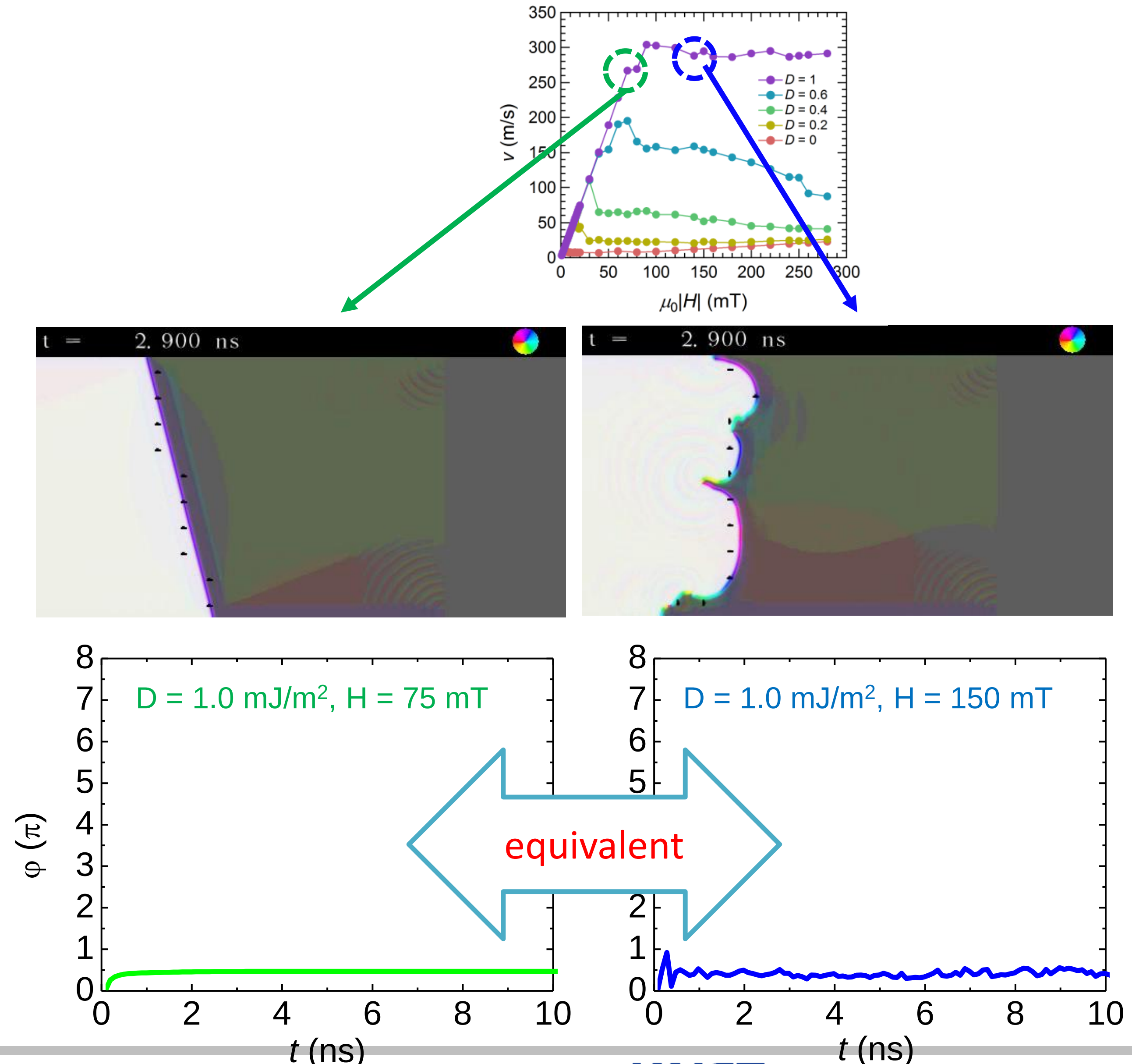
❖ Locking of the azimuthal angle of DW under DMI



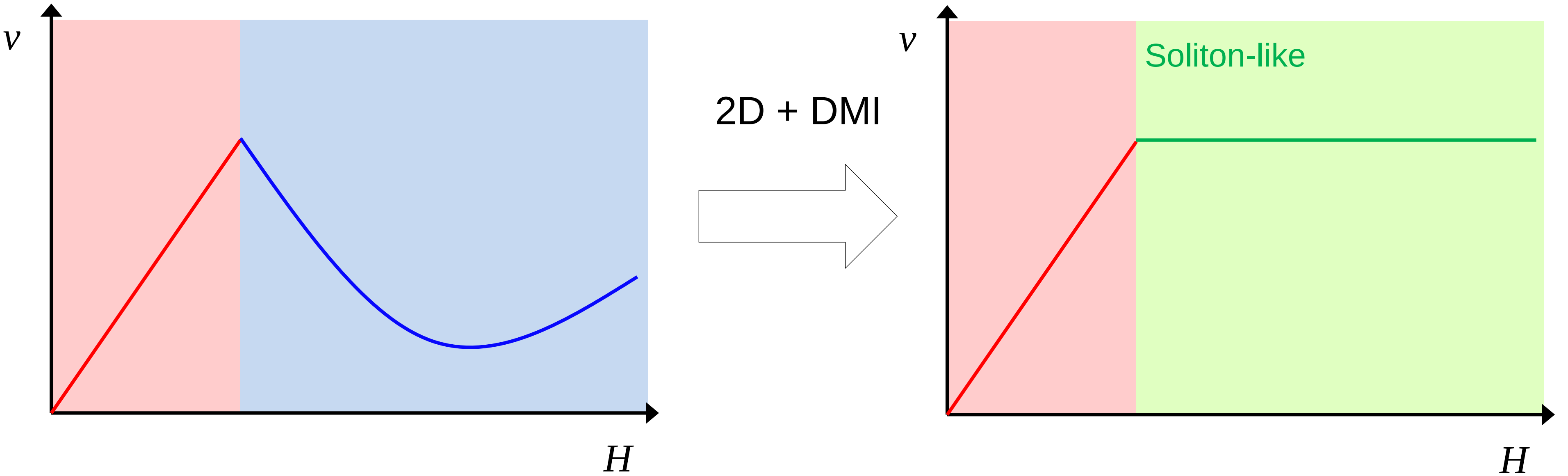


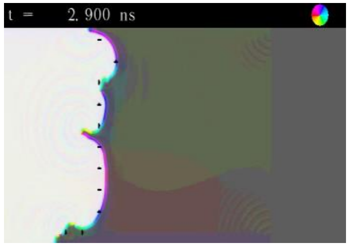


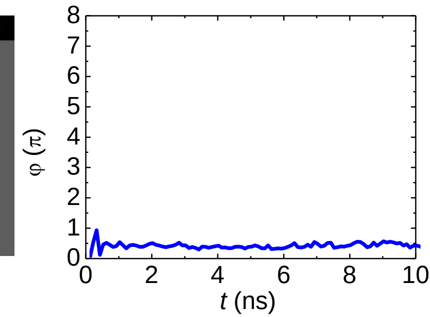
❖ Locking of the azimuthal angle of DW under DMI



❖ Soliton-like DW motion even above the Walker field



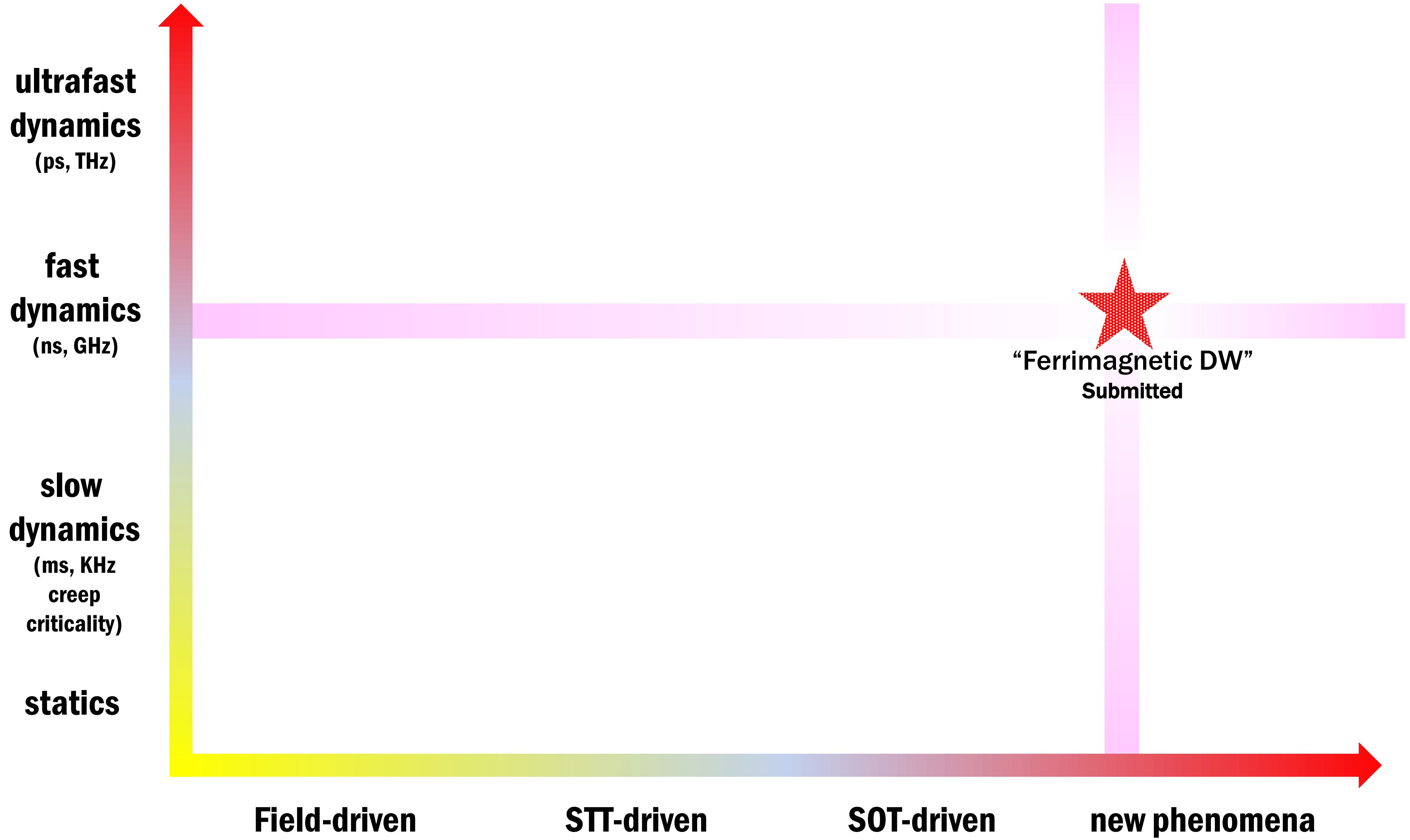




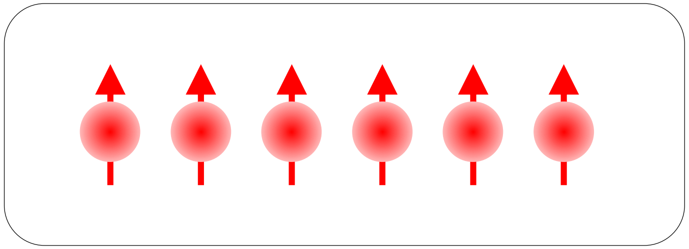
Soliton-like → Locally, precessional motion
As a whole, steady motion

Yoshimura, KJK et al. Nat. Phys. (2015)

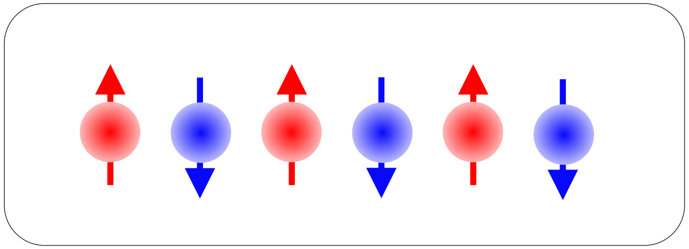
❖ Today's topic is…



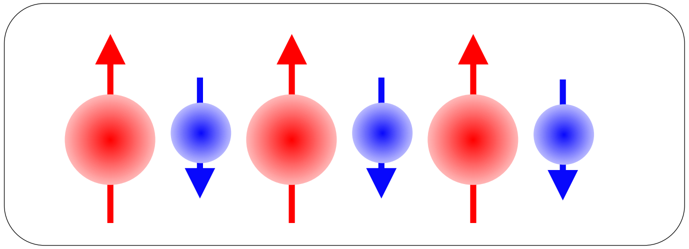
❖ Class of magnet



Ferromagnet



Antiferromagnet

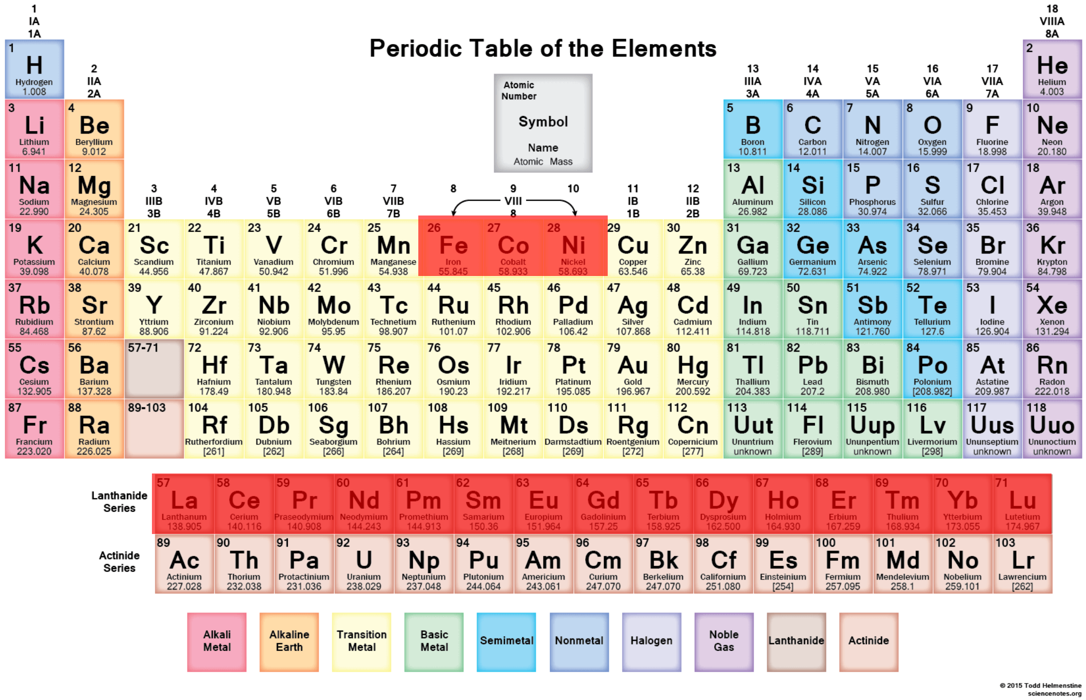


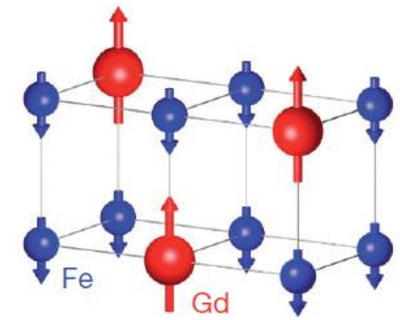
Ferrimagnet

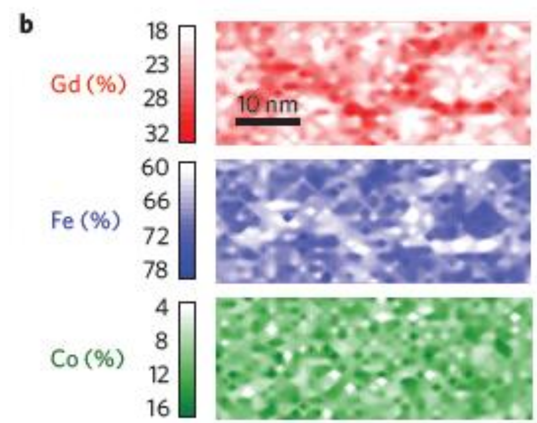
Microscopically antiferromagnet
Macroscopically ferromagnet

⇨ **Possible to control by magnetic field**

❖ Transition Metal-Rare Earth ferrimagnet







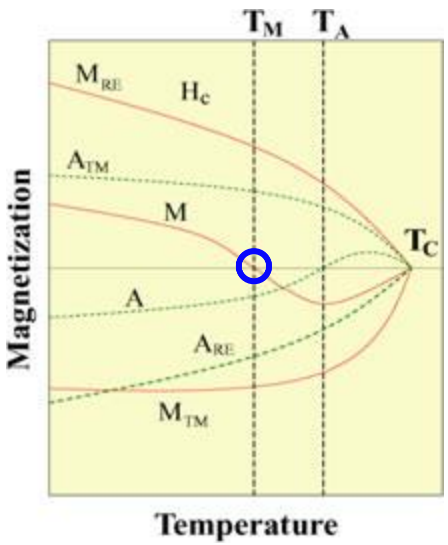
Transition Metal – Rare Earth Ferrimagnets

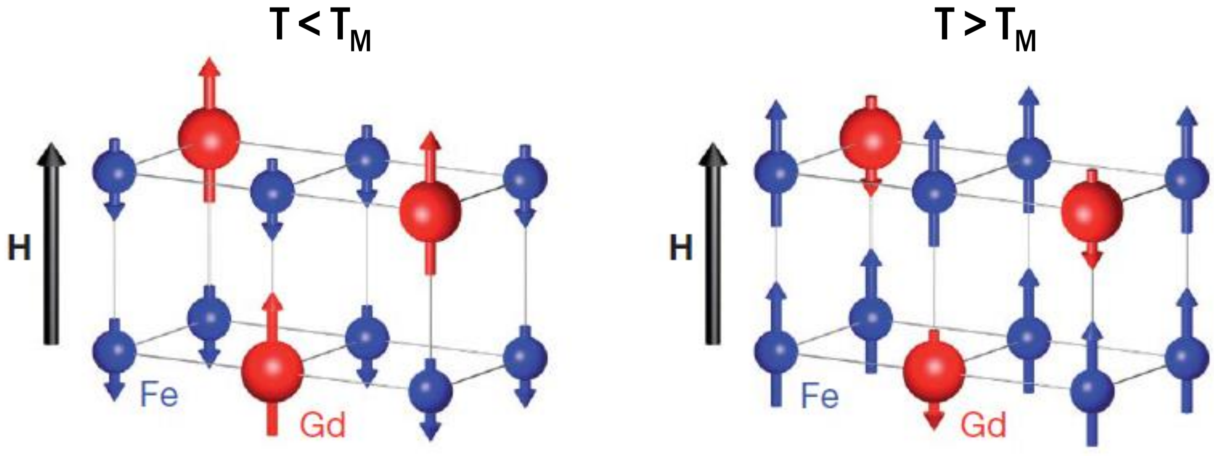
Two sublattices are antiparallel

Amorphous

Radu et al. Nature. ***472****, 205 (2011)*
C.E.Graves et al. Nat. Mater. ***12****, 293 (2013)*

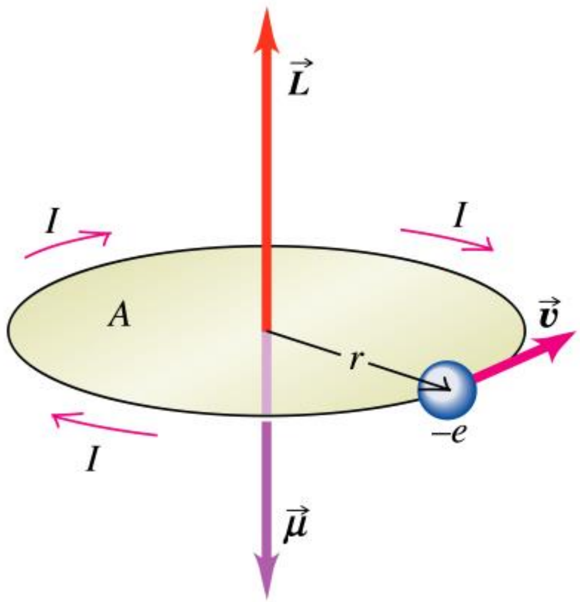
❖ T_M of ferrimagnet





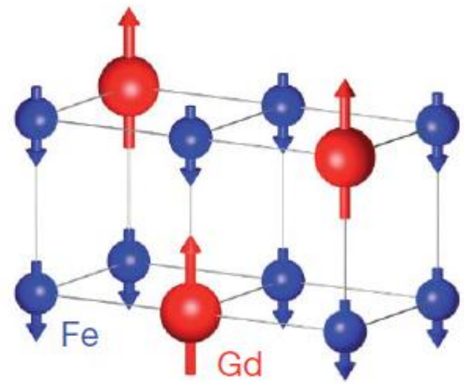
T_M : Magnetization compensation temperature

❖ Another compensation temperature: T_A



$$\vec{\mu} = \gamma \vec{L}$$

$$\gamma = \frac{g\mu_B}{\hbar}$$

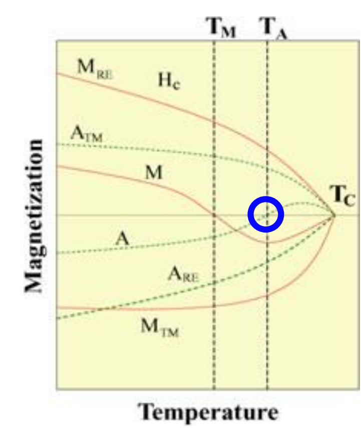


$$g_{\mathrm{Gd}} \neq g_{\mathrm{Fe}} \longrightarrow \gamma_{\mathrm{Gd}} \neq \gamma_{\mathrm{Fe}}$$

$$\mathrm{T_M} : \vec{\mu}_{\mathrm{Gd}} + \vec{\mu}_{\mathrm{Fe}} = \gamma_{\mathrm{Gd}} \vec{L}_{\mathrm{Gd}} + \gamma_{\mathrm{Fe}} \vec{L}_{\mathrm{Fe}} = 0$$

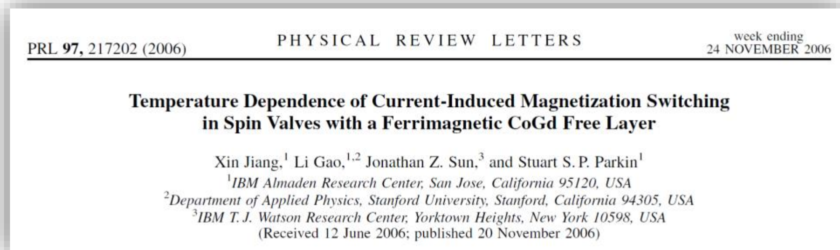
$$\mathrm{T_A} : \vec{L}_{\mathrm{Gd}} + \vec{L}_{\mathrm{Fe}} = 0$$

$$\therefore \mathrm{T_M} \neq \mathrm{T_A}$$



T_A : Angular momentum compensation temperature

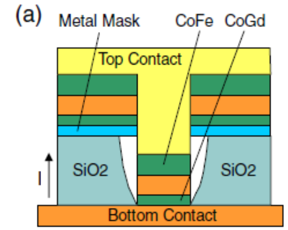
❖ Previous studies on T_A

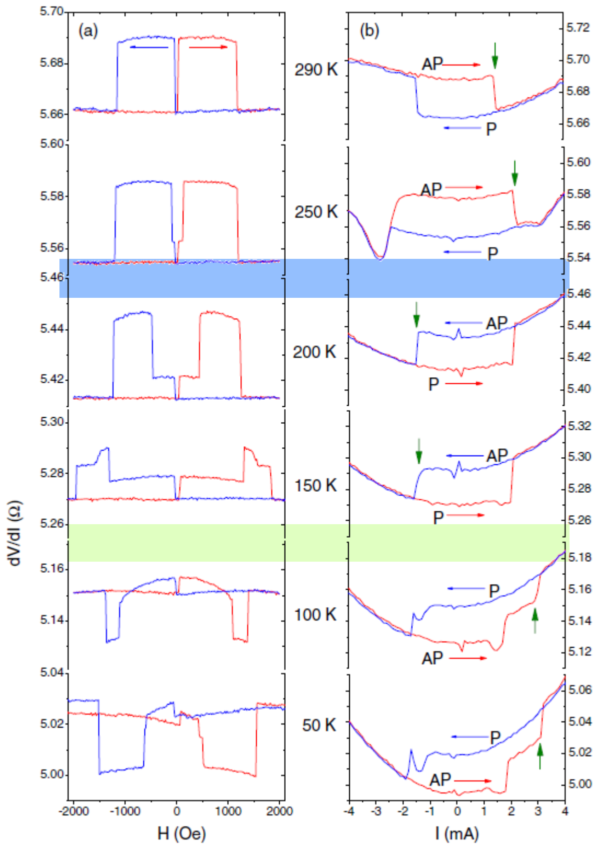


PRL **97,** 217202 (2006) PHYSICAL REVIEW LETTERS week ending 24 NOVEMBER 2006

Temperature Dependence of Current-Induced Magnetization Switching in Spin Valves with a Ferrimagnetic CoGd Free Layer

Xin Jiang,[1] Li Gao,[1,2] Jonathan Z. Sun,[3] and Stuart S. P. Parkin[1]
[1]*IBM Almaden Research Center, San Jose, California 95120, USA*
[2]*Department of Applied Physics, Stanford University, Stanford, California 94305, USA*
[3]*IBM T. J. Watson Research Center, Yorktown Heights, New York 10598, USA*
(Received 12 June 2006; published 20 November 2006)



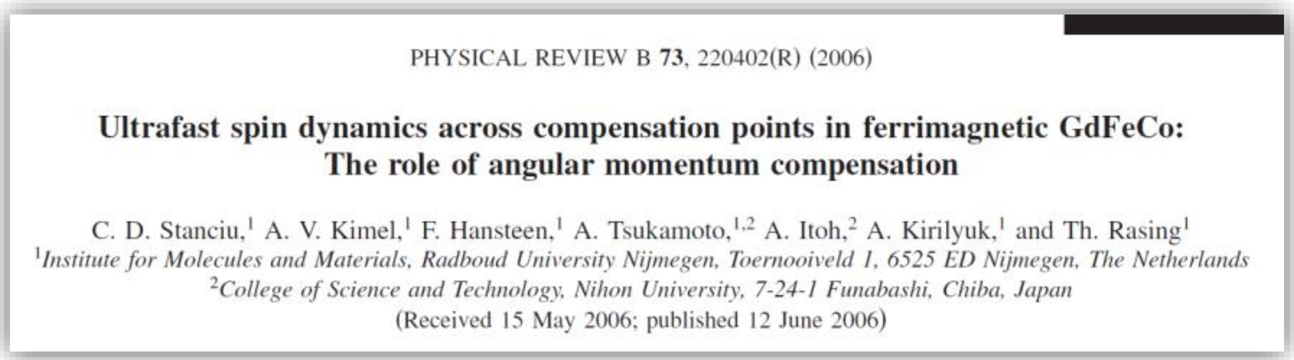


T_A : Angular momentum compensation temperature

T_M : Magnetization compensation temperature

X. Jiang et al. PRL ***97****, 217202 (2006)*

❖ Previous studies on T_A



PHYSICAL REVIEW B **73**, 220402(R) (2006)

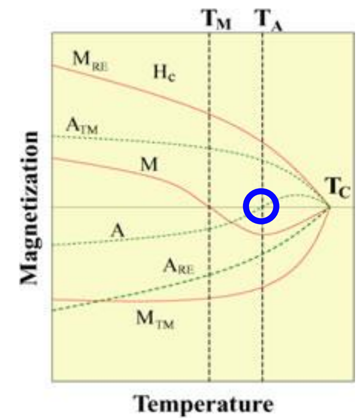
Ultrafast spin dynamics across compensation points in ferrimagnetic GdFeCo: The role of angular momentum compensation

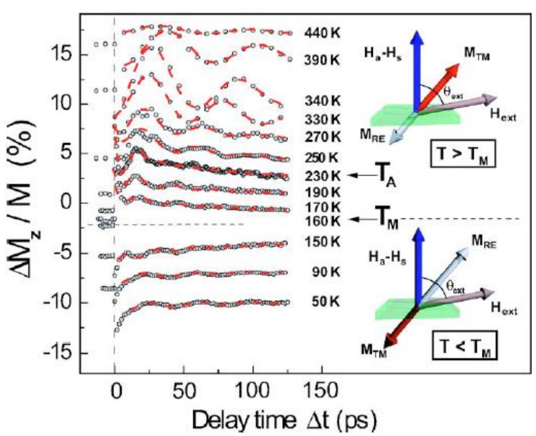
C. D. Stanciu,[1] A. V. Kimel,[1] F. Hansteen,[1] A. Tsukamoto,[1,2] A. Itoh,[2] A. Kirilyuk,[1] and Th. Rasing[1]

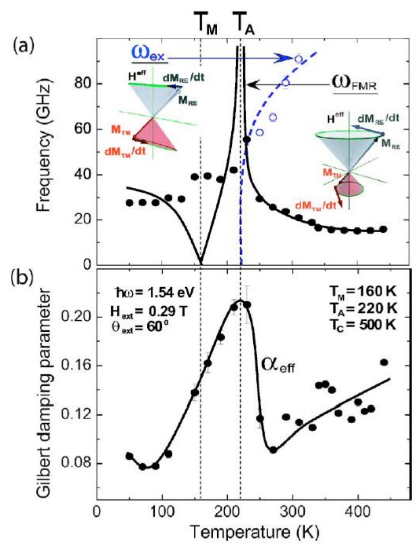
[1]*Institute for Molecules and Materials, Radboud University Nijmegen, Toernooiveld 1, 6525 ED Nijmegen, The Netherlands*

[2]*College of Science and Technology, Nihon University, 7-24-1 Funabashi, Chiba, Japan*

(Received 15 May 2006; published 12 June 2006)





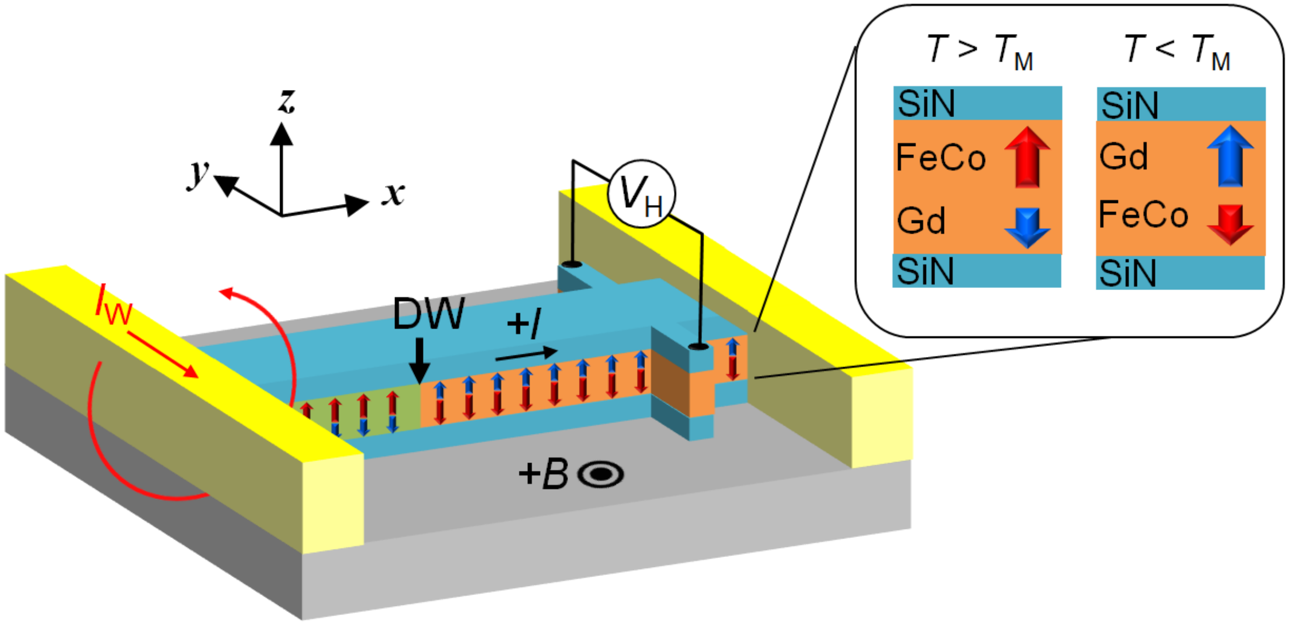


*C. D. Stanciu et al. PRB **73**, 220402(R) (2006)*

$$\gamma = \frac{\vec{\mu}_{total}}{\vec{L}_{total}} \quad \begin{matrix} \longrightarrow \text{finite} \\ \longrightarrow = 0 \end{matrix}$$

If then, DW velocity also diverges!

❖ Let's check it!



SiN (5 nm)

GdFeCo (30 nm)

SiN (5 nm)

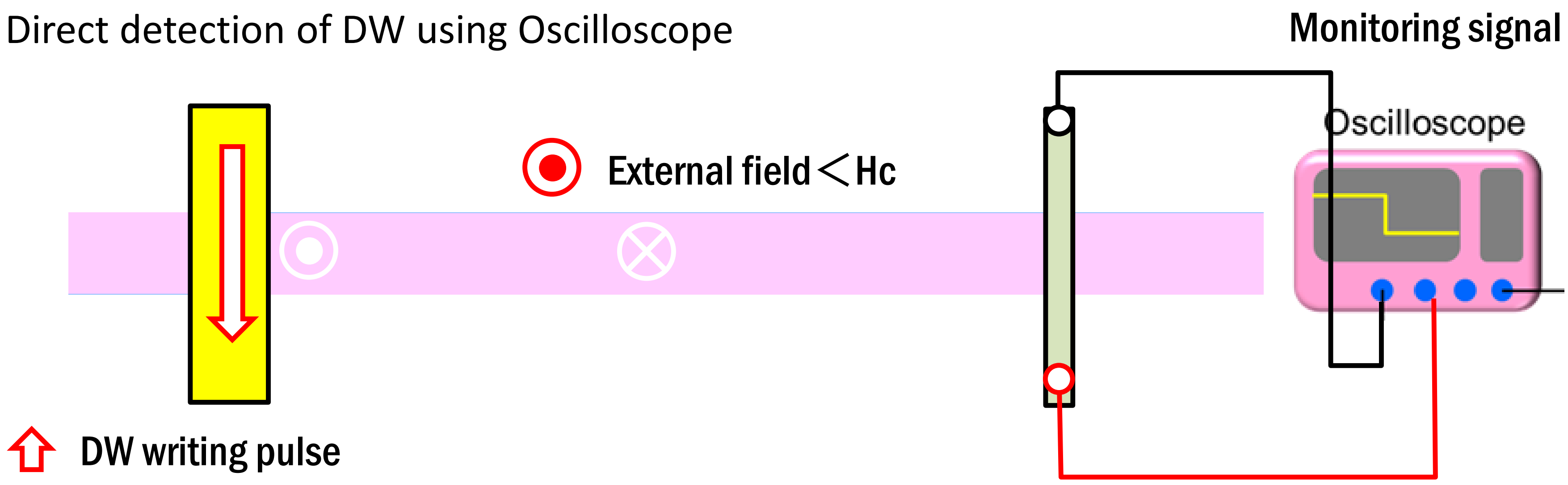
Films (Tsukamoto group @ Nihon University)

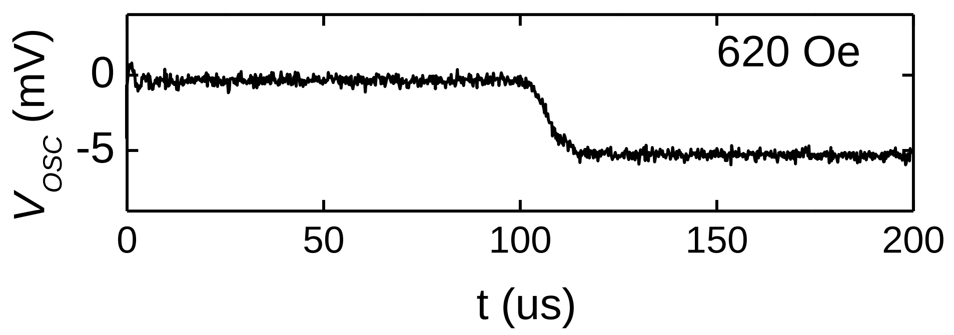
Patterning and measurement (Ono group @ Kyoto University)

❖ How the measure?

Real-time DW detection technique

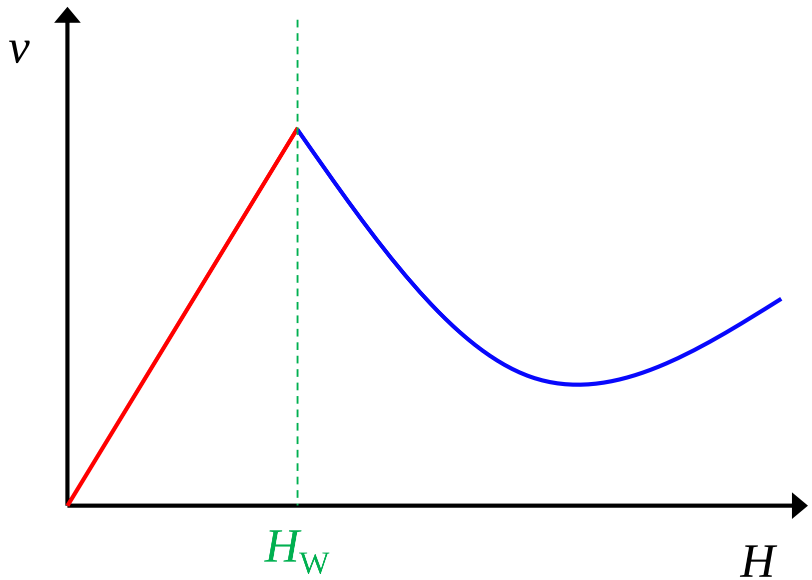
→ Direct detection of DW using Oscilloscope





Remove the rising time of magnetic field

❖ Why the DW velocity is enhanced at T_A?



Precessional regime

$$v = \gamma\Delta \frac{\alpha}{1+\alpha^2} H$$

Steady regime

$$v = \frac{\gamma\Delta}{\alpha} H$$

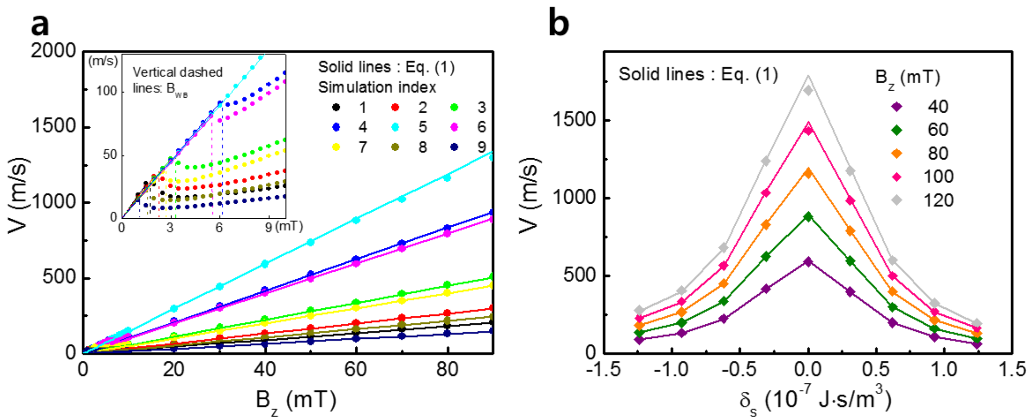
Walker breakdown field

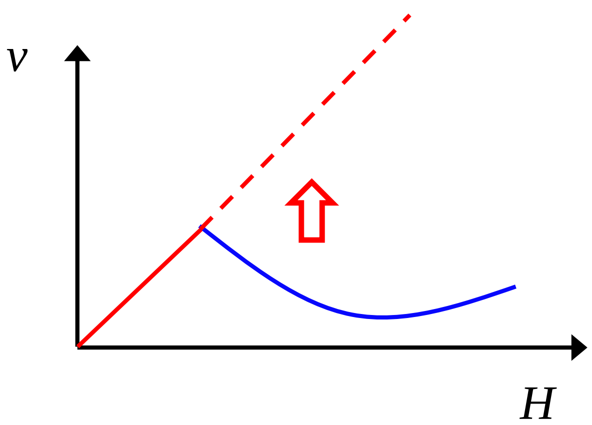
$$H_W = 2\pi\alpha M_S \left| N_y - N_x \right|$$

❖ Why the DW velocity is enhanced at T_A ?

By S.-H. Oh, K-J Lee
Korea University

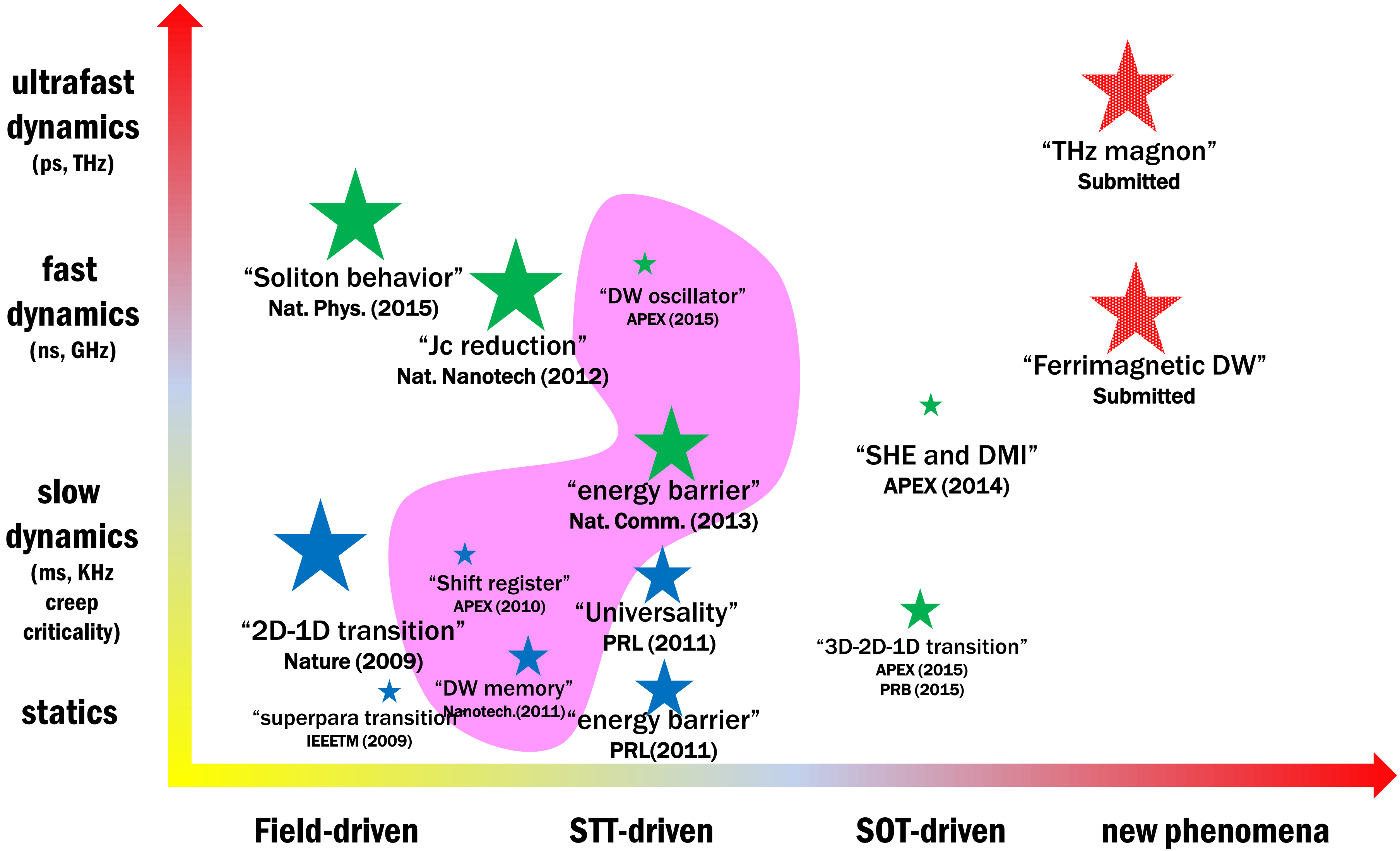
Micromagnetic simulation reproduces the exp. result.



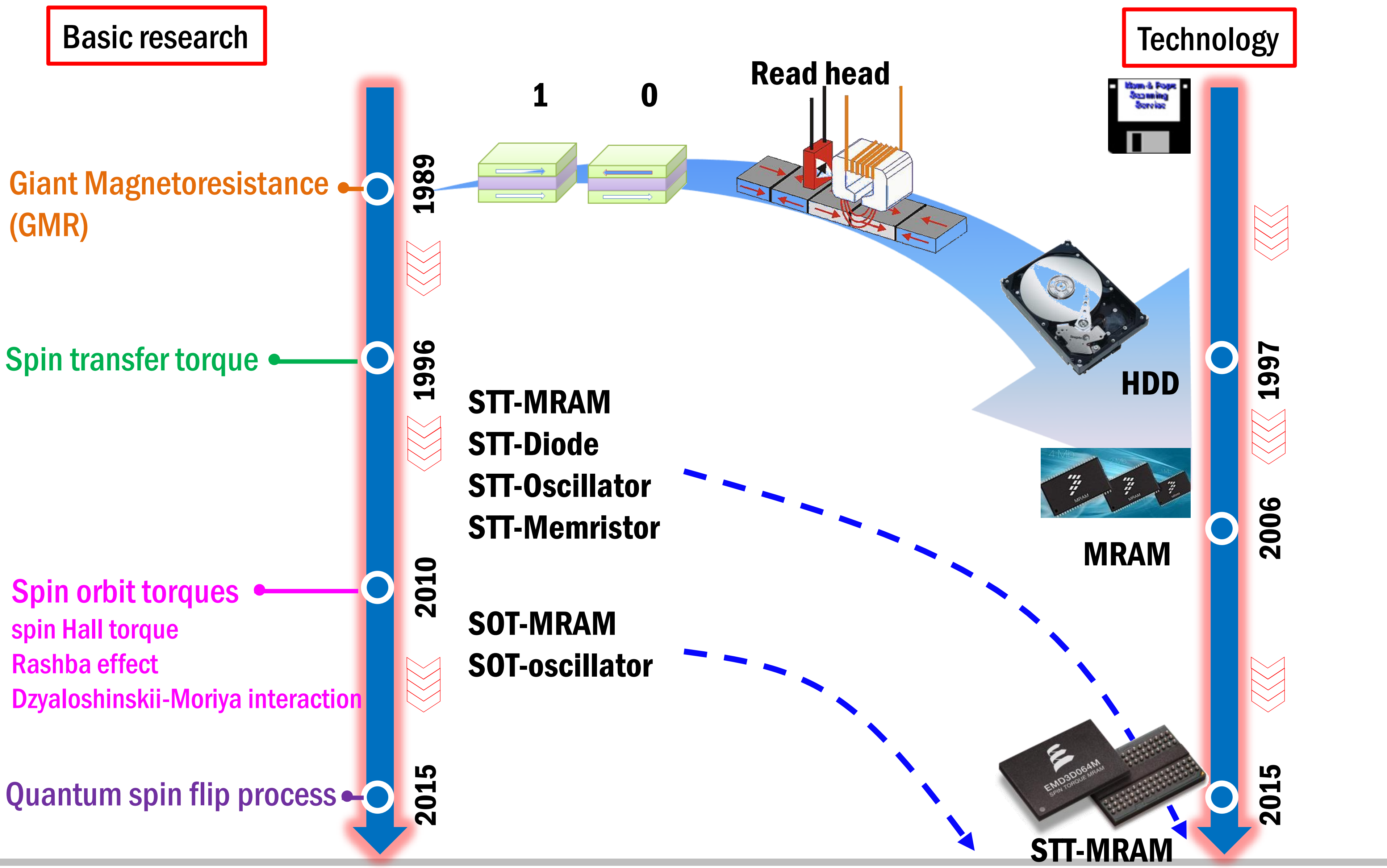


Precessional motion → Steady motion at T_A

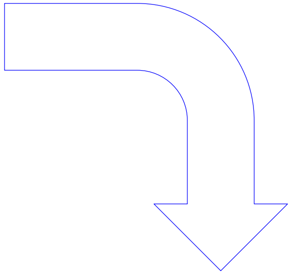
❖ Applied physics?

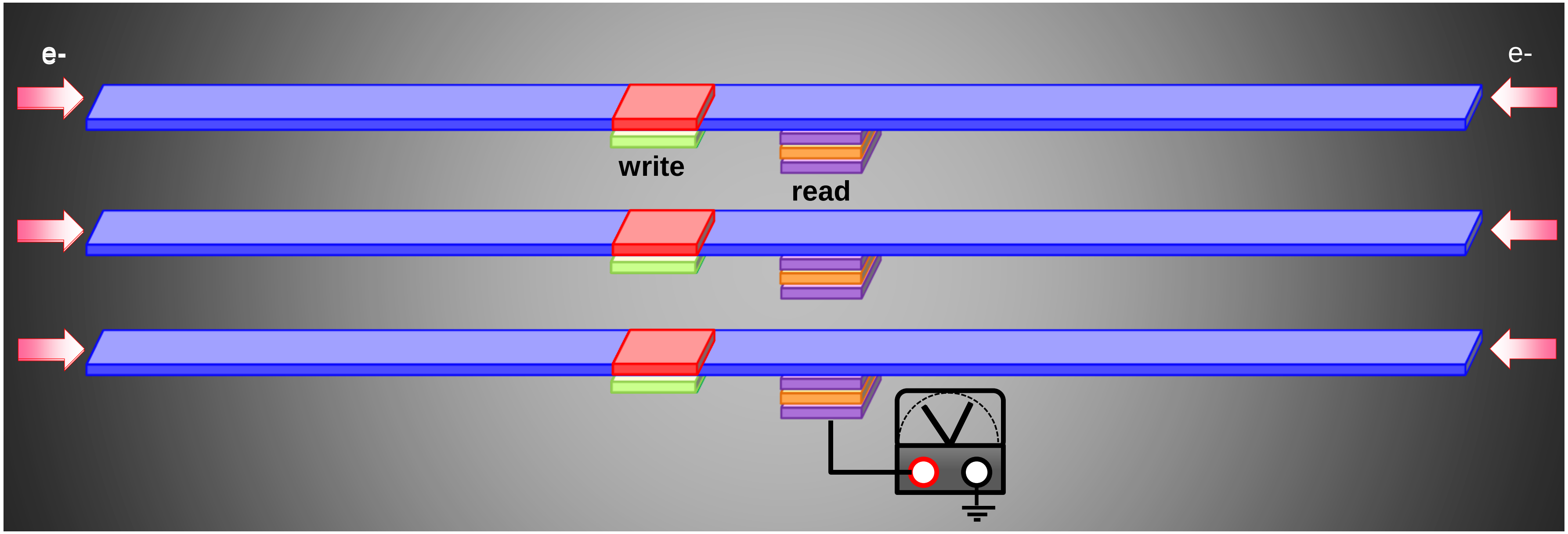


❖ Applied physics?



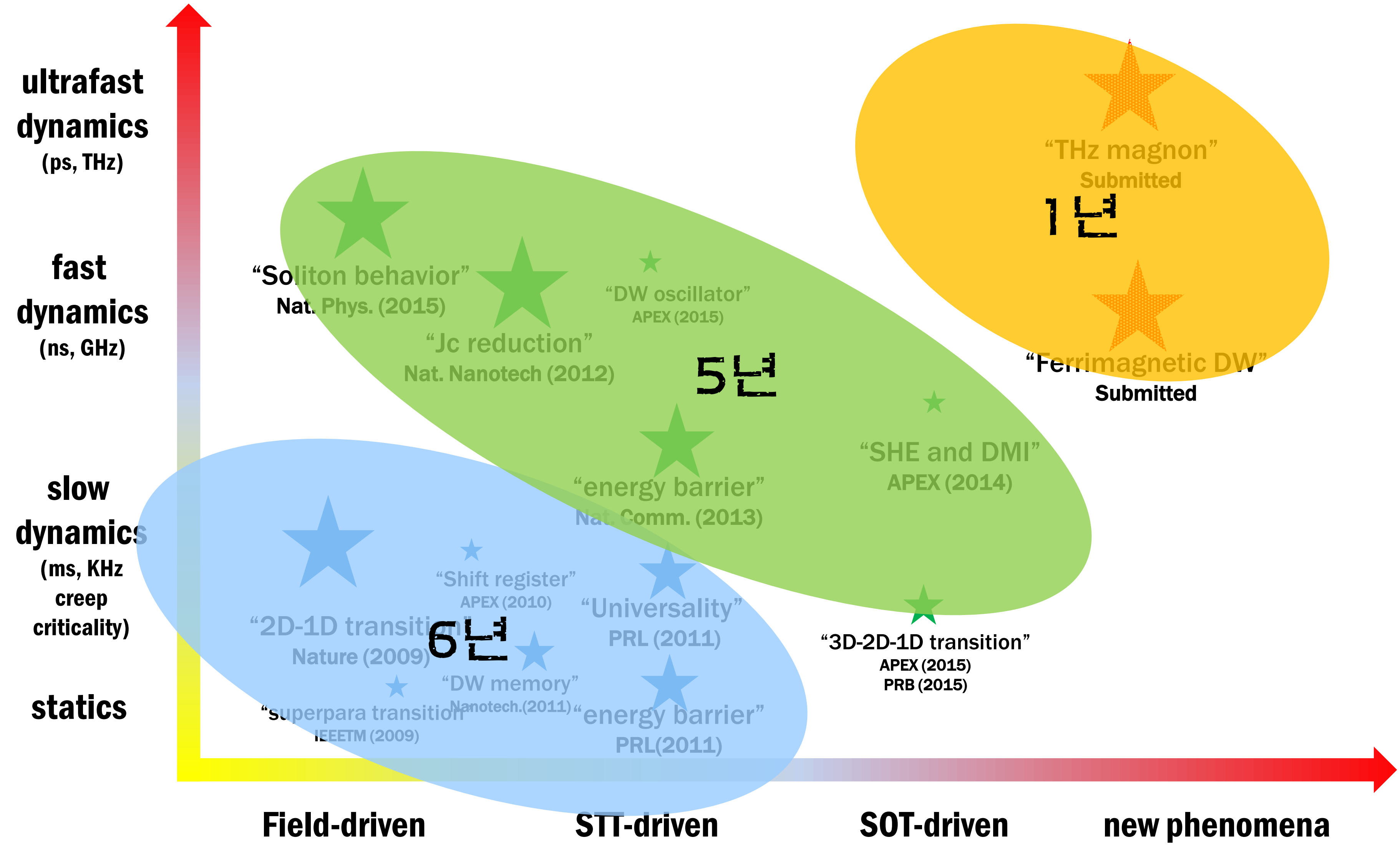
❖ Next generation magnetic memory





❖ Summary

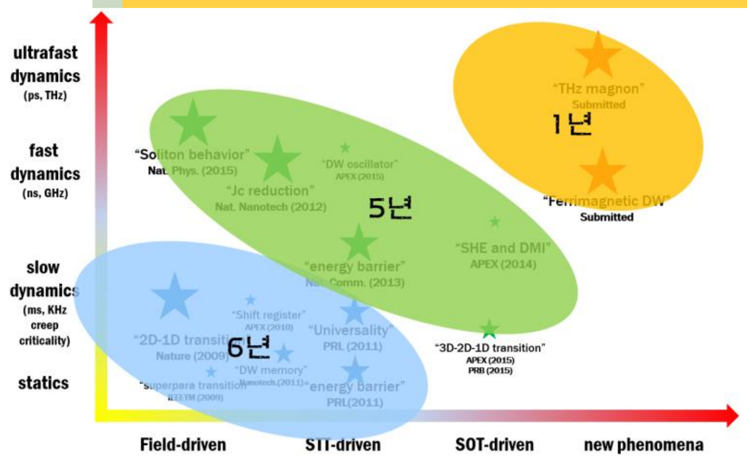
During last 12years…



❖ Future plan

나에겐 아직 30년의 시간이 있습니다.

이 공간을 여러분과 함께 채워가고 싶습니다.



고맙습니다.