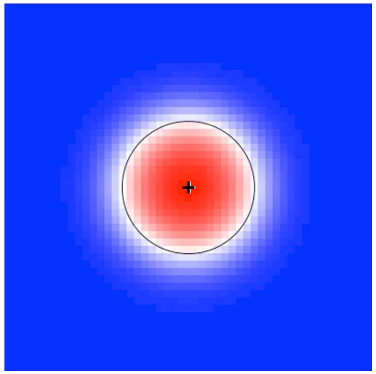
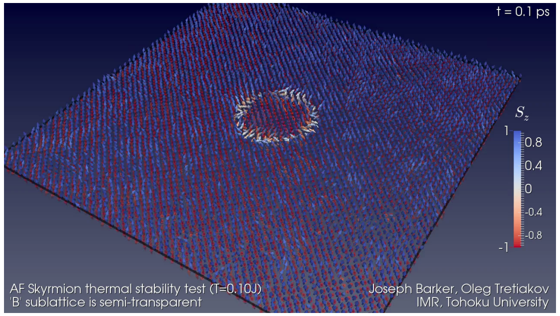
# Antiferromagnetic Skyrmions



***Oleg Tretiakov***




***Institute for Materials Research, Tohoku University, Japan***

NPSMP-2015, U. of Tokyo, Kashiwa; June 16, 2015

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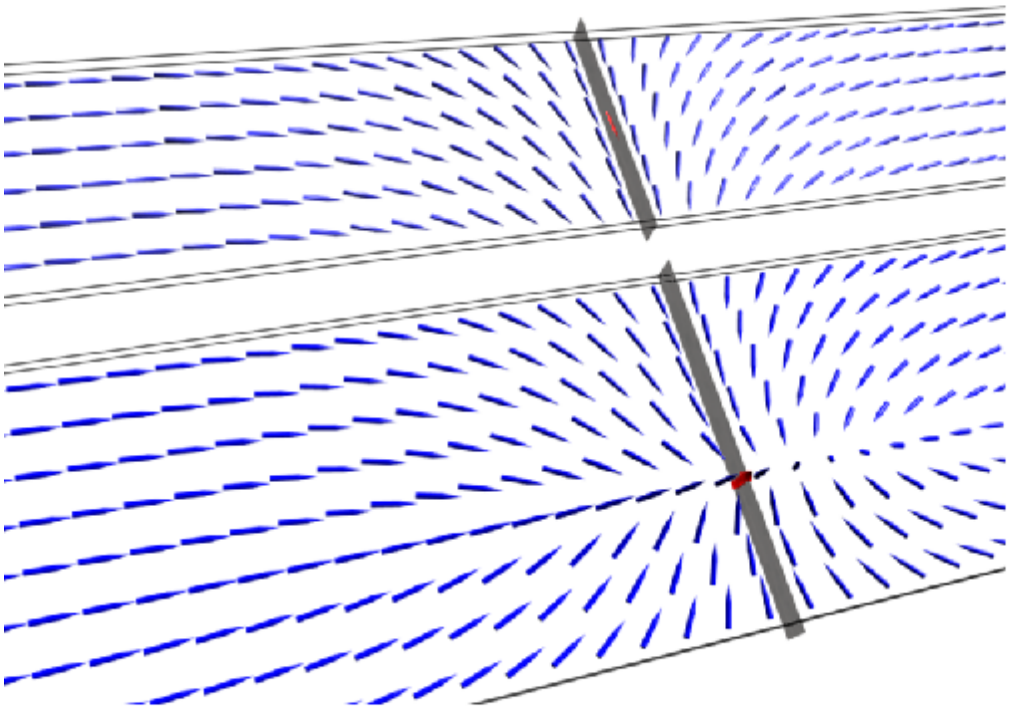
*Grant Support:*

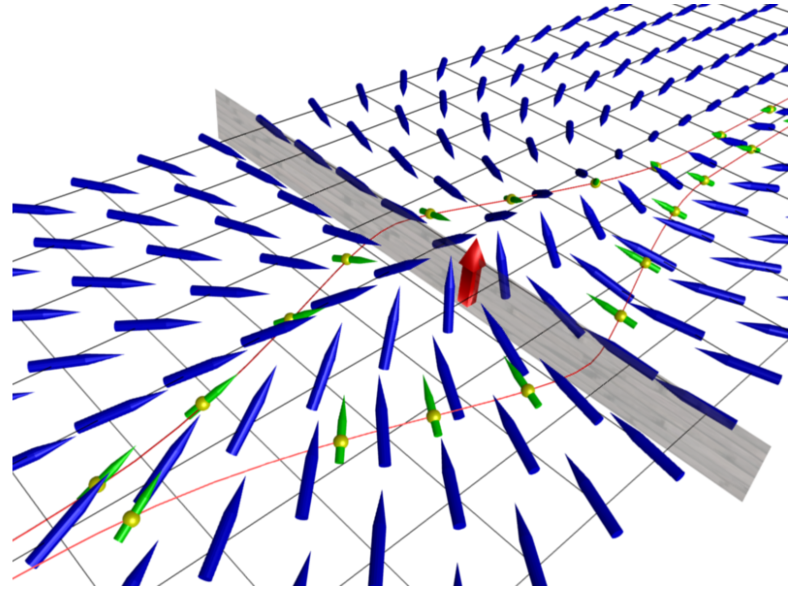
Nano Spin Conversion Science

JSPS

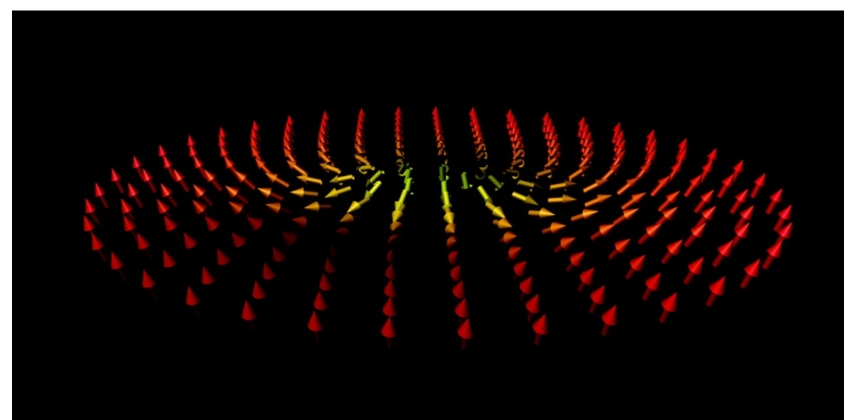
Japan Society for the Promotion of Science

# Intro: topological textures





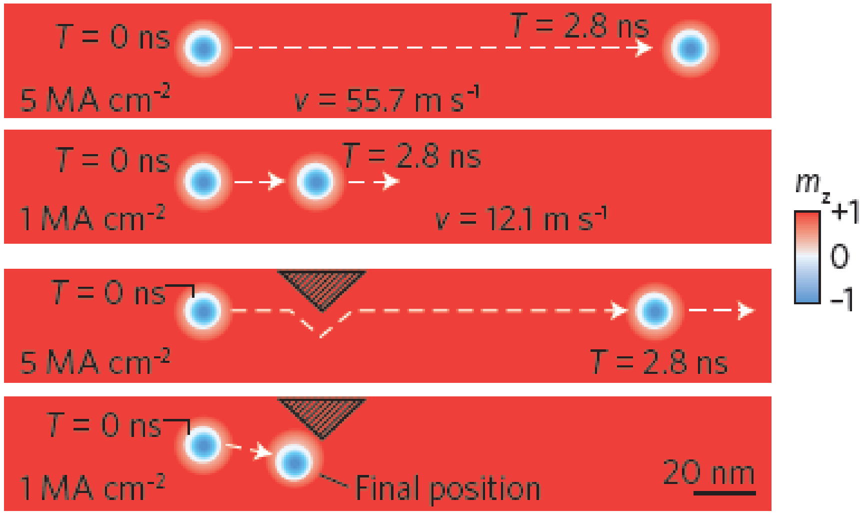
skyrmionic spin texture:



- Different soft mode(s)

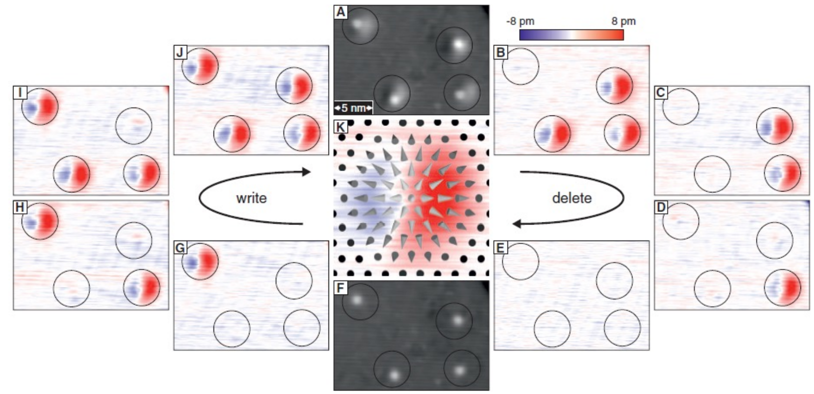
# Recent Progress: Single Skyrmions

## Skyrmion motion induced by current (simulations)



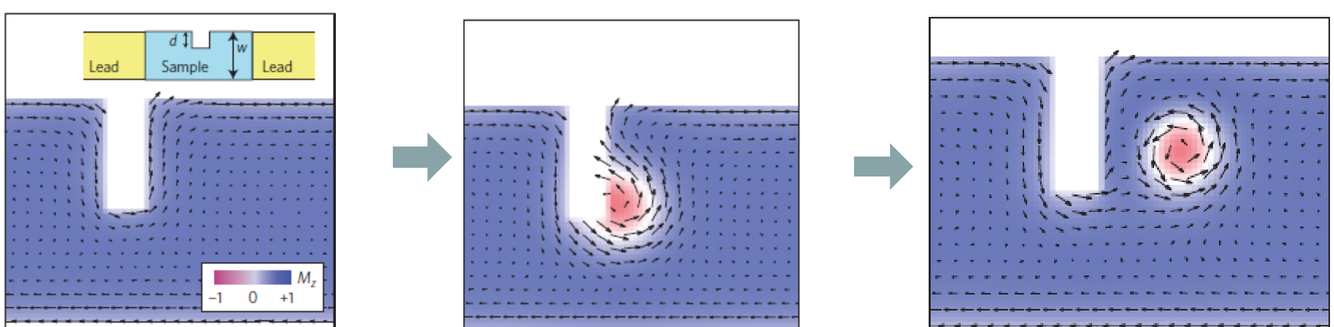

J. Sampaio et.al, Nat. Nanotech. (2013)

## Skyrmion Creation (Experiment)



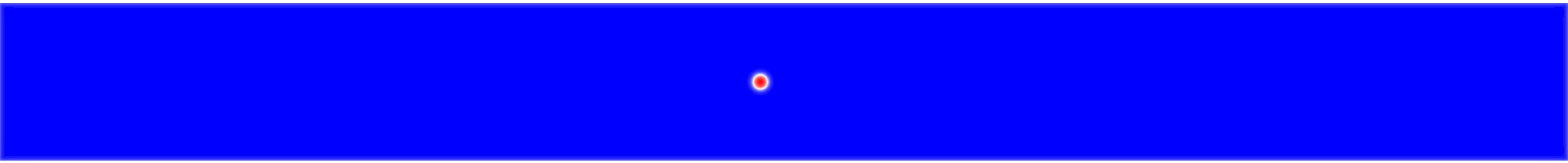

N. Romming et.al, Science (2013)

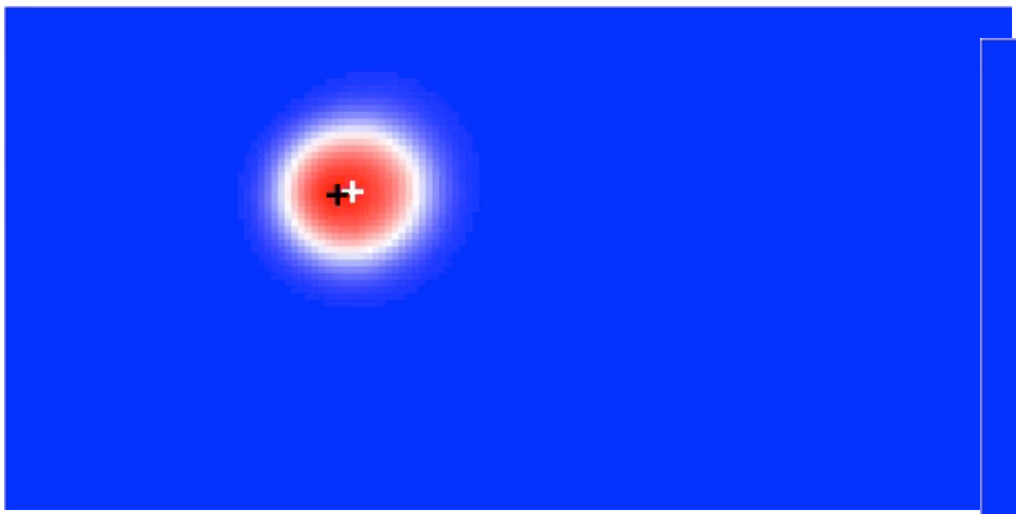
## Skyrmion Creation (simulations)

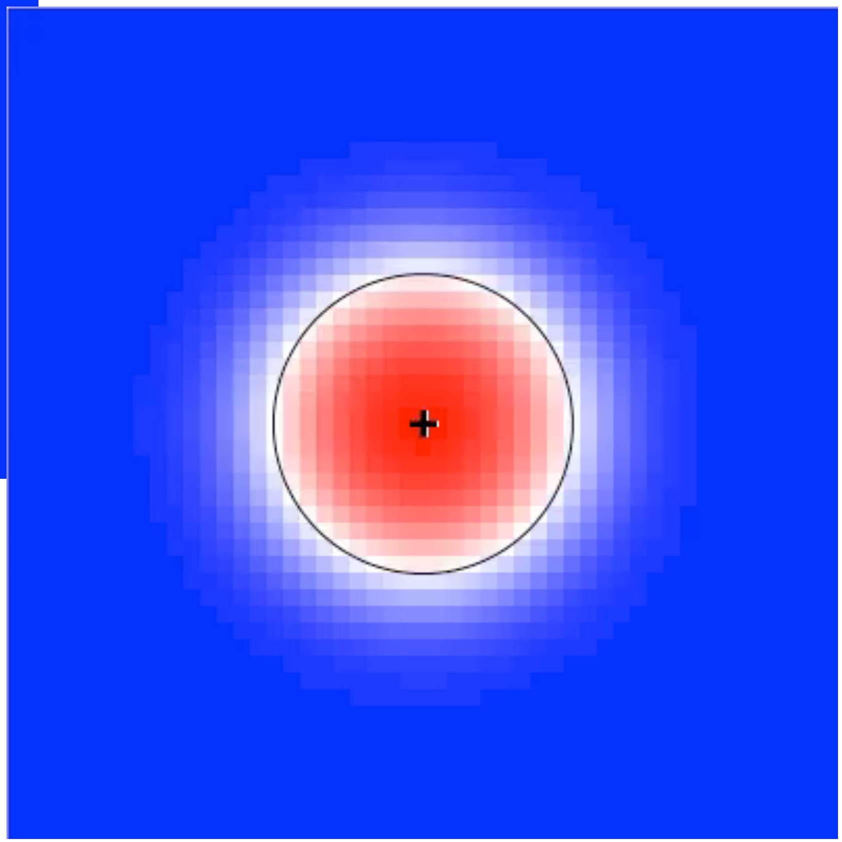



J. Iwasaki et.al, Nat. Nanotech. (2013)

# Internal skyrmion dynamics at high currents





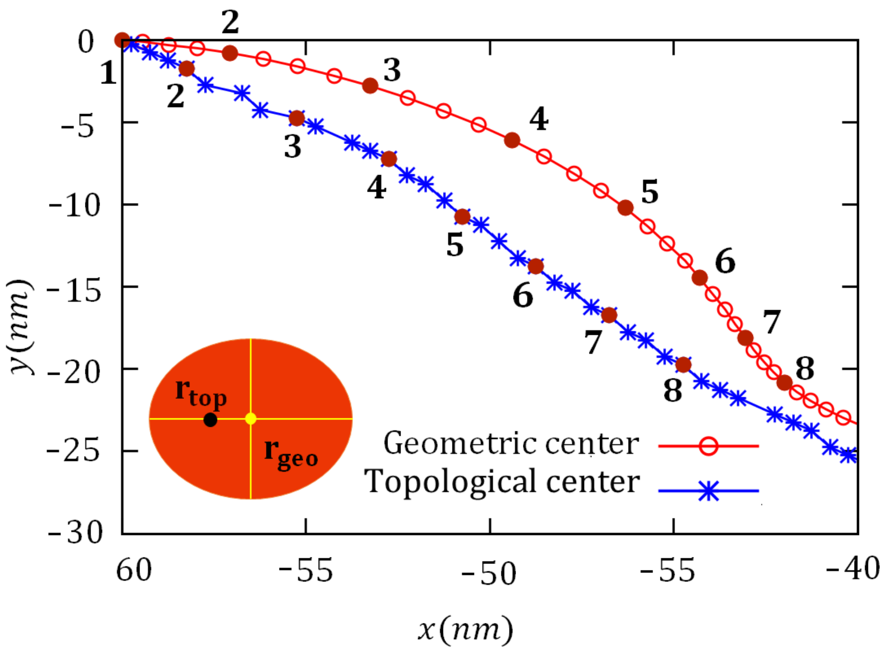


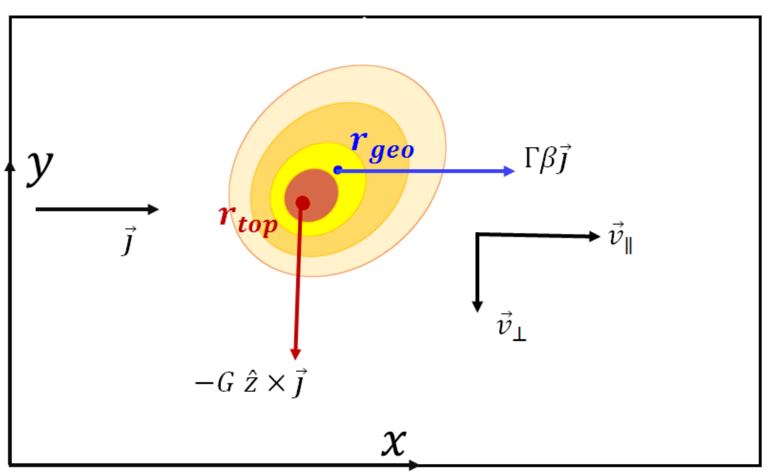
In a deformed skyrmion
there are 2 centers:
Topological and geometric

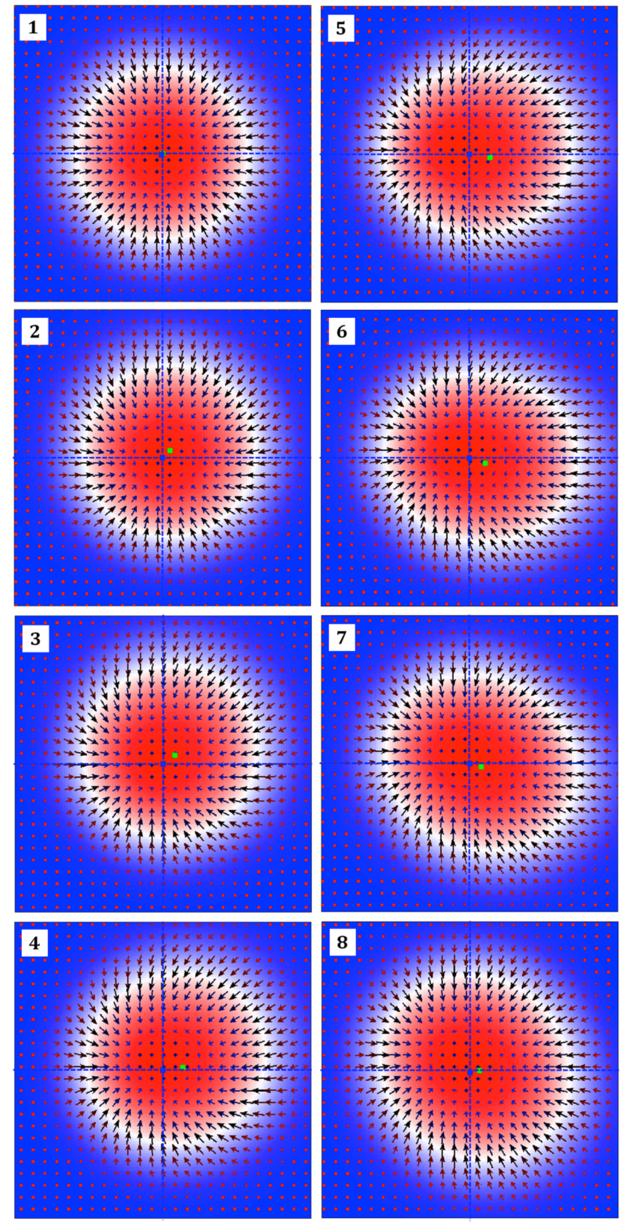
Their motion obeys different generalized Thiele's equations.

# Internal Skyrmion Dynamics

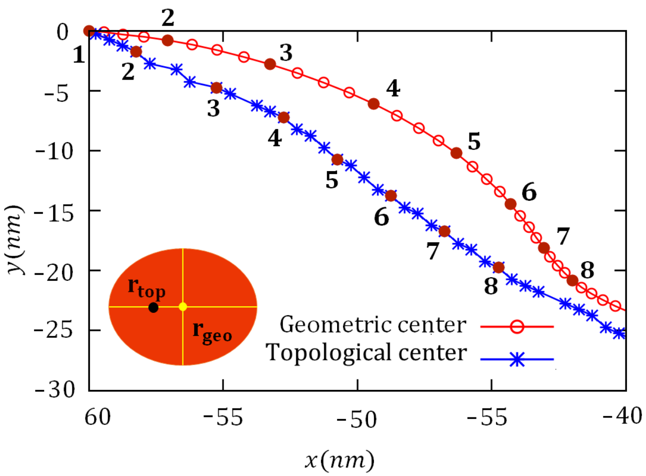
Trajectories of skyrmion centers:



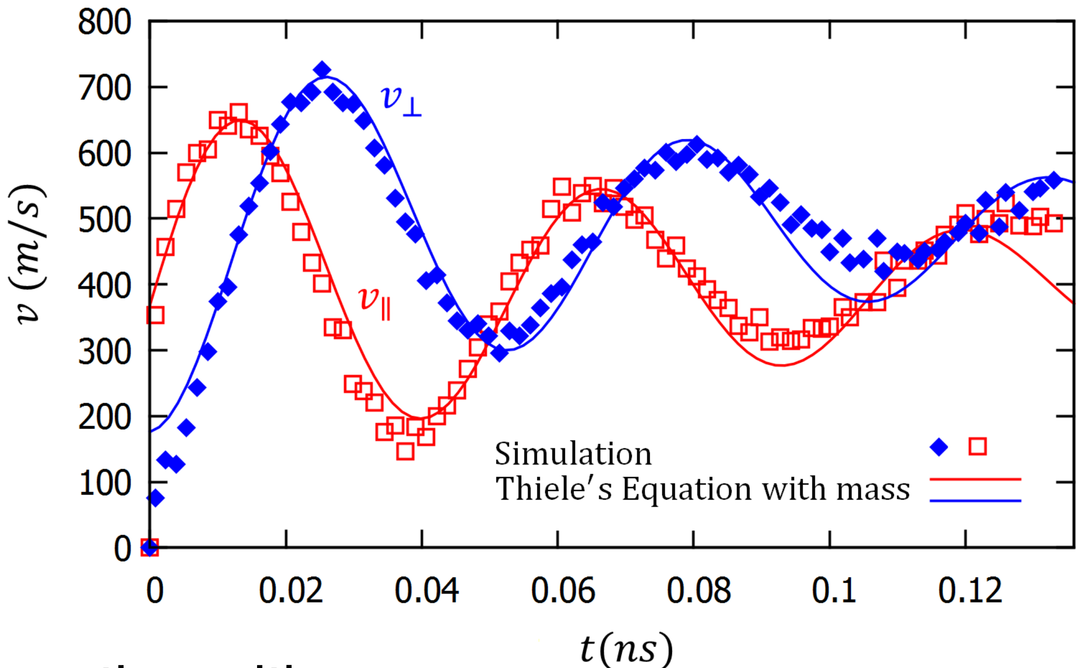



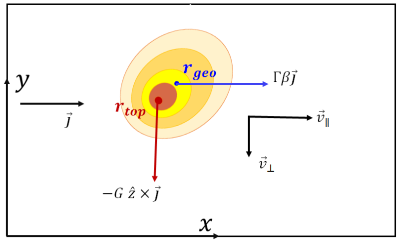



# Internal Skyrmion Dynamics




Velocity of skyrmion's geometric center:




Thiele's equation with mass:

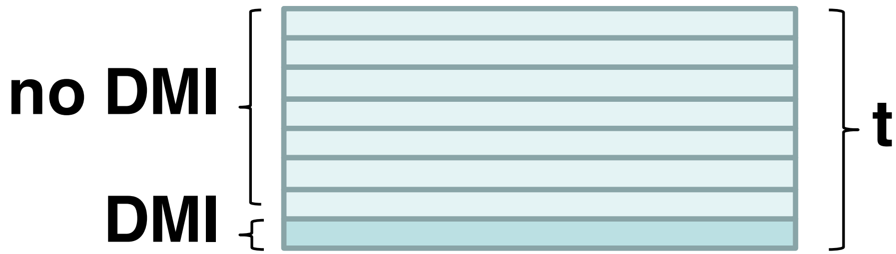
$$m\frac{d\vec{v}(t)}{dt} + \Gamma\alpha\vec{v}(t) - G\hat{z}\times\vec{v}(t) = \Gamma\beta\vec{j} - G\hat{z}\times\vec{j}$$

Solution of Thiele's equation:

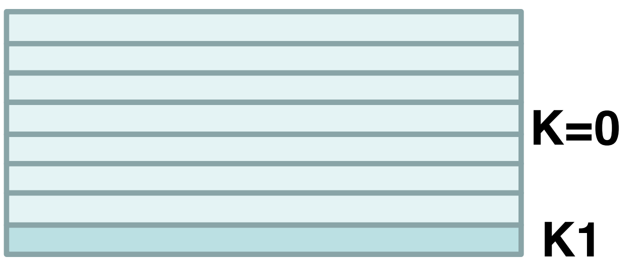
$$v_{||,\perp}(t) = Ae^{-\frac{t}{T(m)}}\cos\left(\omega(m)t + \phi\right)$$

# Skyrmions in Multilayers

## Types of structures:

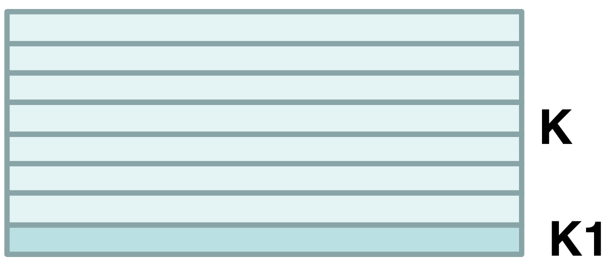



**1.**



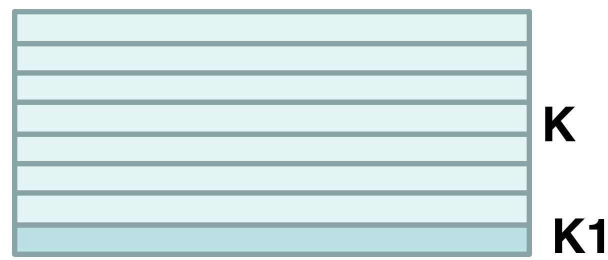

**Interface DMI**
**K1**
**K=0**

**2.**




**Interface DMI**
**K1**
**K≠0**

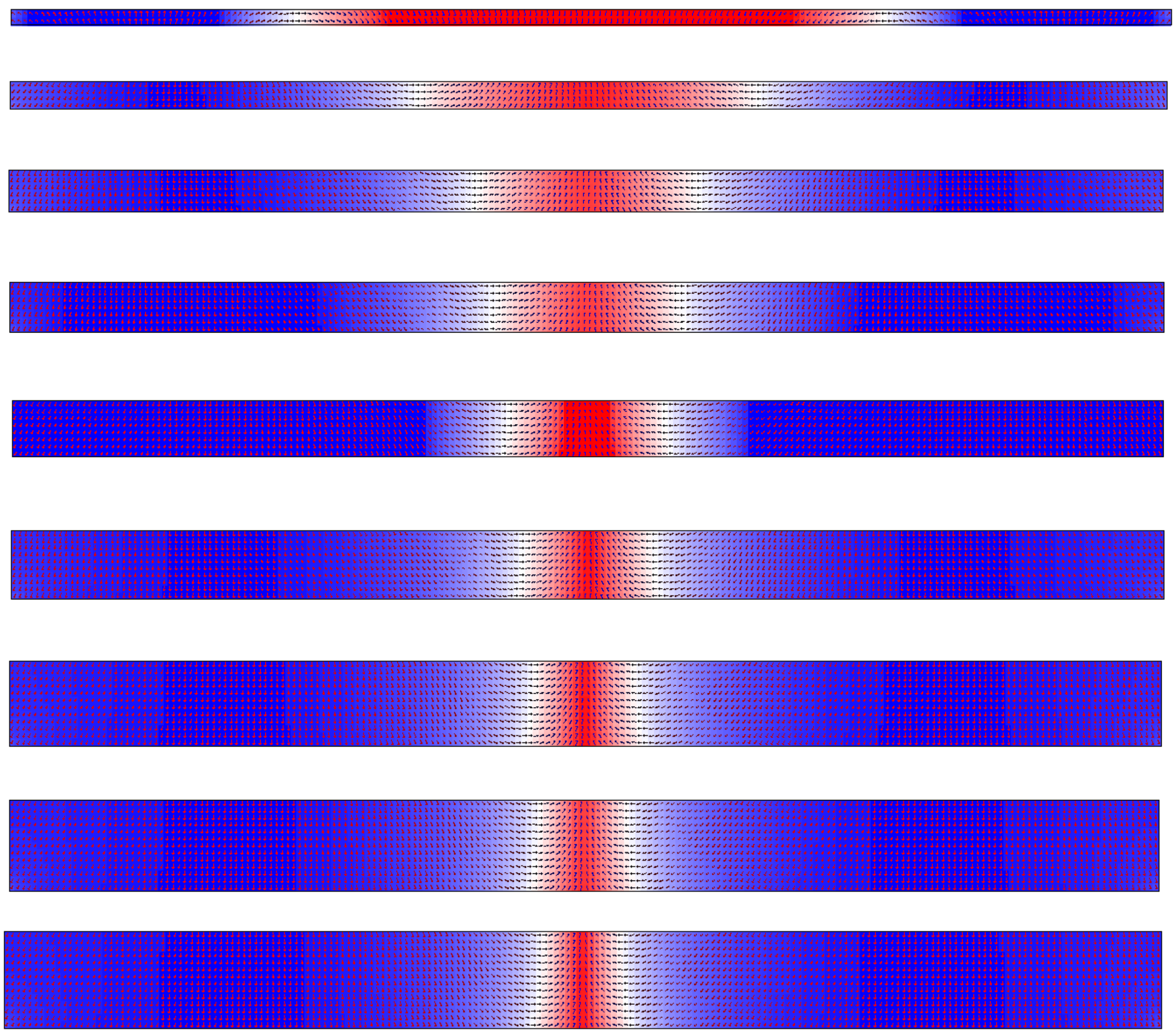
**3.**




**Interface DMI**
**K1**
**K≠0**
$H_{demag}$

# Multilayer skyrmions: thickness dependence

$D/D_C=1.95$ $(D=7.0)$



N=2 (1.2 nm), r=50 at. cells

N=4 (2.4 nm), r=29 at. cells

N=6 (3.6 nm), r=19 at. cells

N=7 (4.2 nm), r=16(15) at. cells

N=8 (4.8 nm), r=14(13) at. cells

N=10 (6.0 nm), r=12(11) at. cells

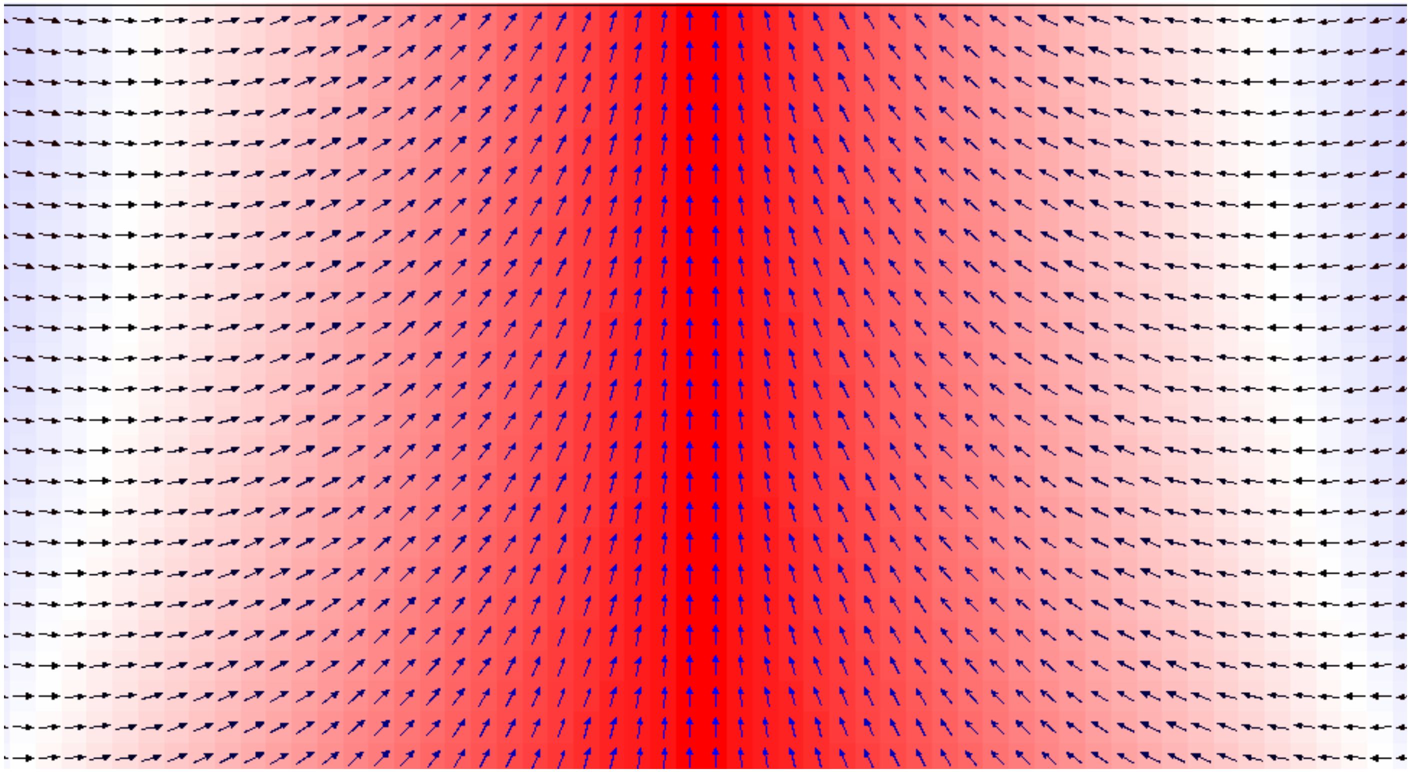
N=12 (7.2 nm), r=10(9) at. cells

N=13 (7.8 nm), r=9(8) at. cells

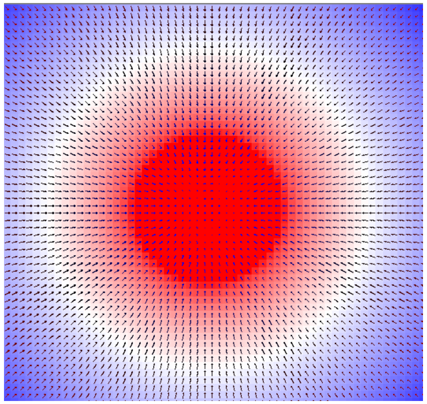
N=14 (8.4 nm), r=8(7) at. cells

# Skyrmions in Multilayers with interface DMI

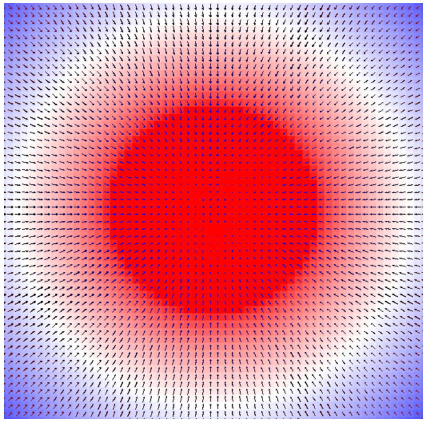
$D/D_C$=3.33, n=25 (t=15 nm)



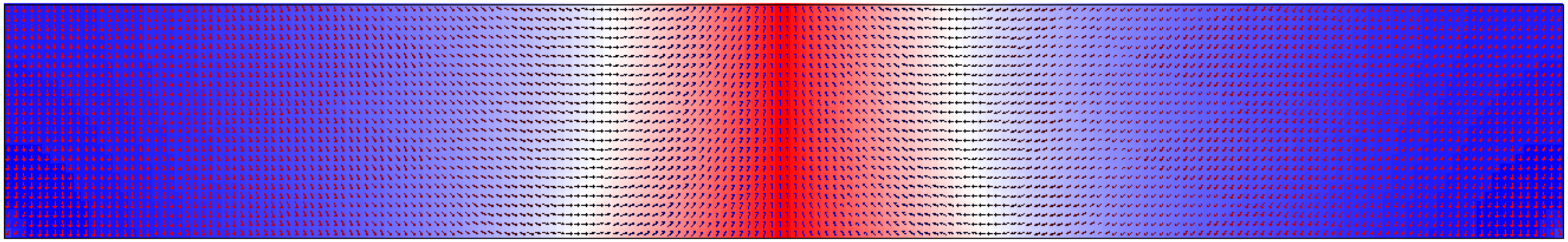
Top



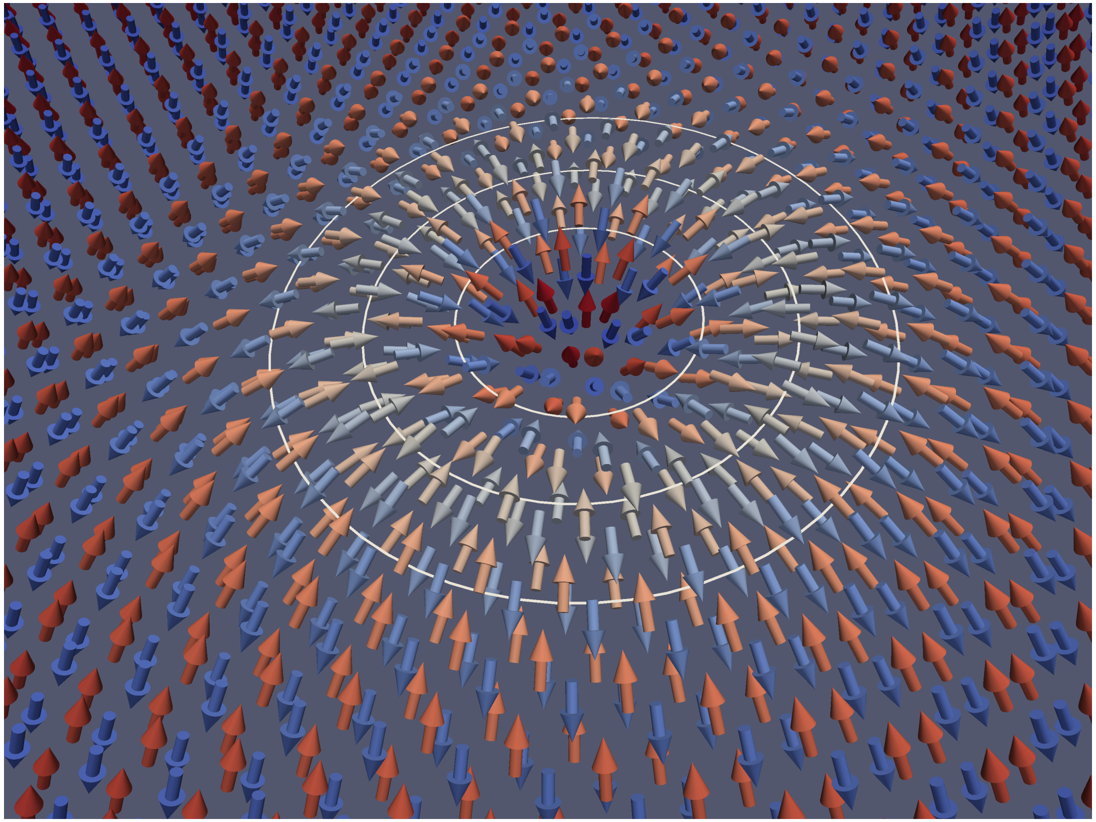
Bottom (DMI)



$R_{bottom}$= 26 at.c., $R_{top}$=22 at.c.

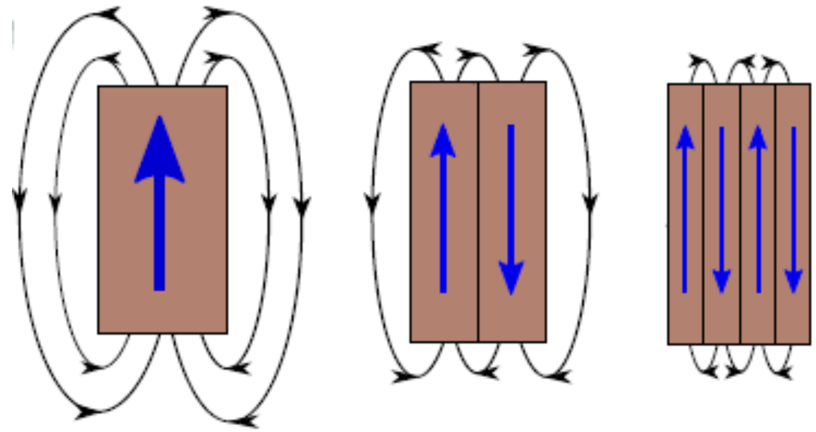


# Antiferromagnetic Skyrmions



# Why AFM Skyrmions?

- AFMs have no stray fields:



- Can be insulating, semiconducting, and metallic.
- Rich spin-wave phenomena.
- Dynamics due to current induced torques.
- Highly ordered spin textures: Skyrmions!

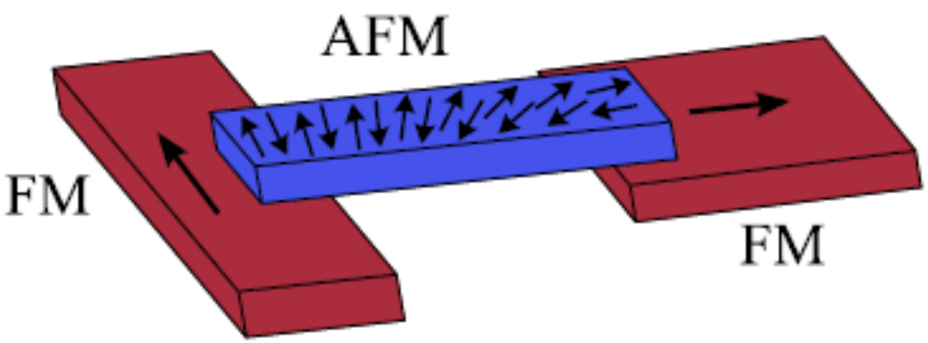
# Texture Dynamics in AFMs

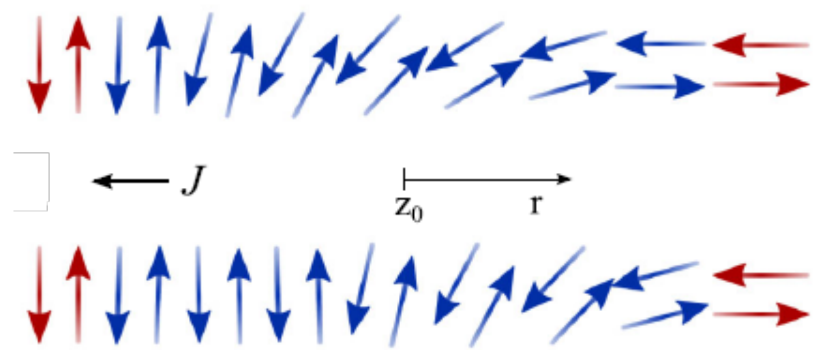
Antiferromagnet:

AFM equations:

$$\dot{\mathbf{n}} = (\gamma \mathbf{f}_m - G_1 \dot{\mathbf{m}}) \times \mathbf{n} + \eta\gamma(\mathbf{J}\cdot\nabla)\mathbf{n},$$

$$\dot{\mathbf{m}} = [\gamma \mathbf{f}_n - G_2 \dot{\mathbf{n}} + \beta\gamma(\mathbf{J}\cdot\nabla)\mathbf{n}] \times \mathbf{n} + T_{nl},$$



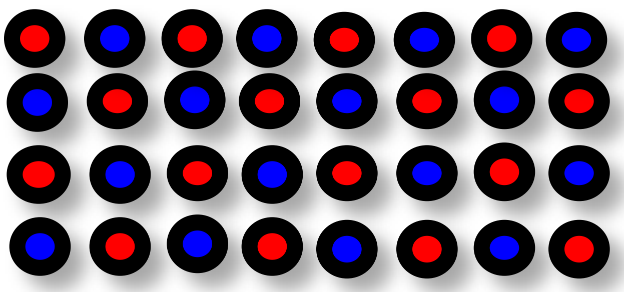

Damped harmonic oscillator:

$$M\ddot{r} + \Gamma\dot{r} + M\omega_0^2 r = F_J + F_H,$$

ı veten, Qaiumzadeh, Tretiakov, Brataas, PRL (2013)
Kim, Tserkovnyak, Tchernyshyov PRB (2014)

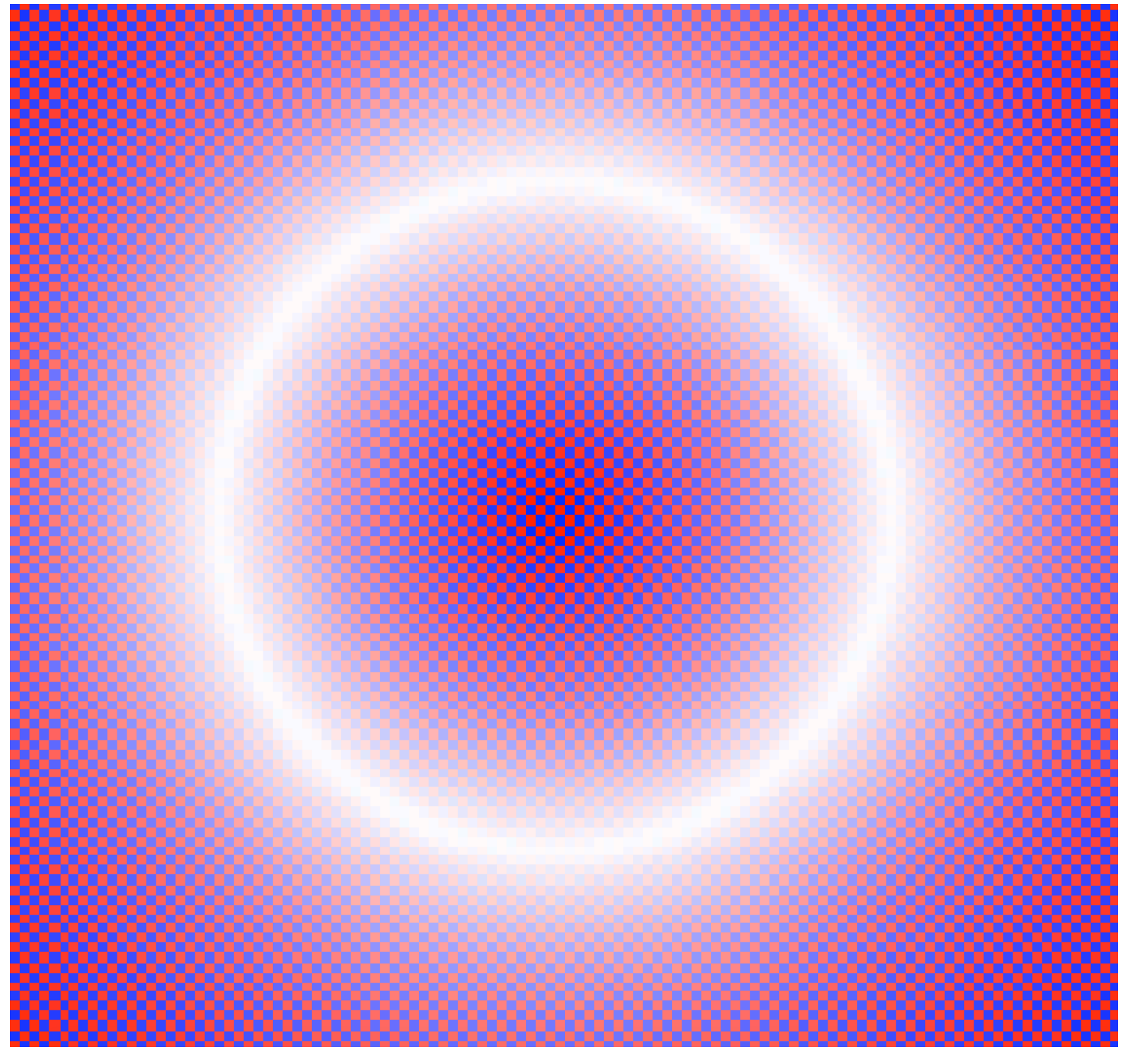
# Large AFM Skyrmion

**G-type antiferromagnet:**

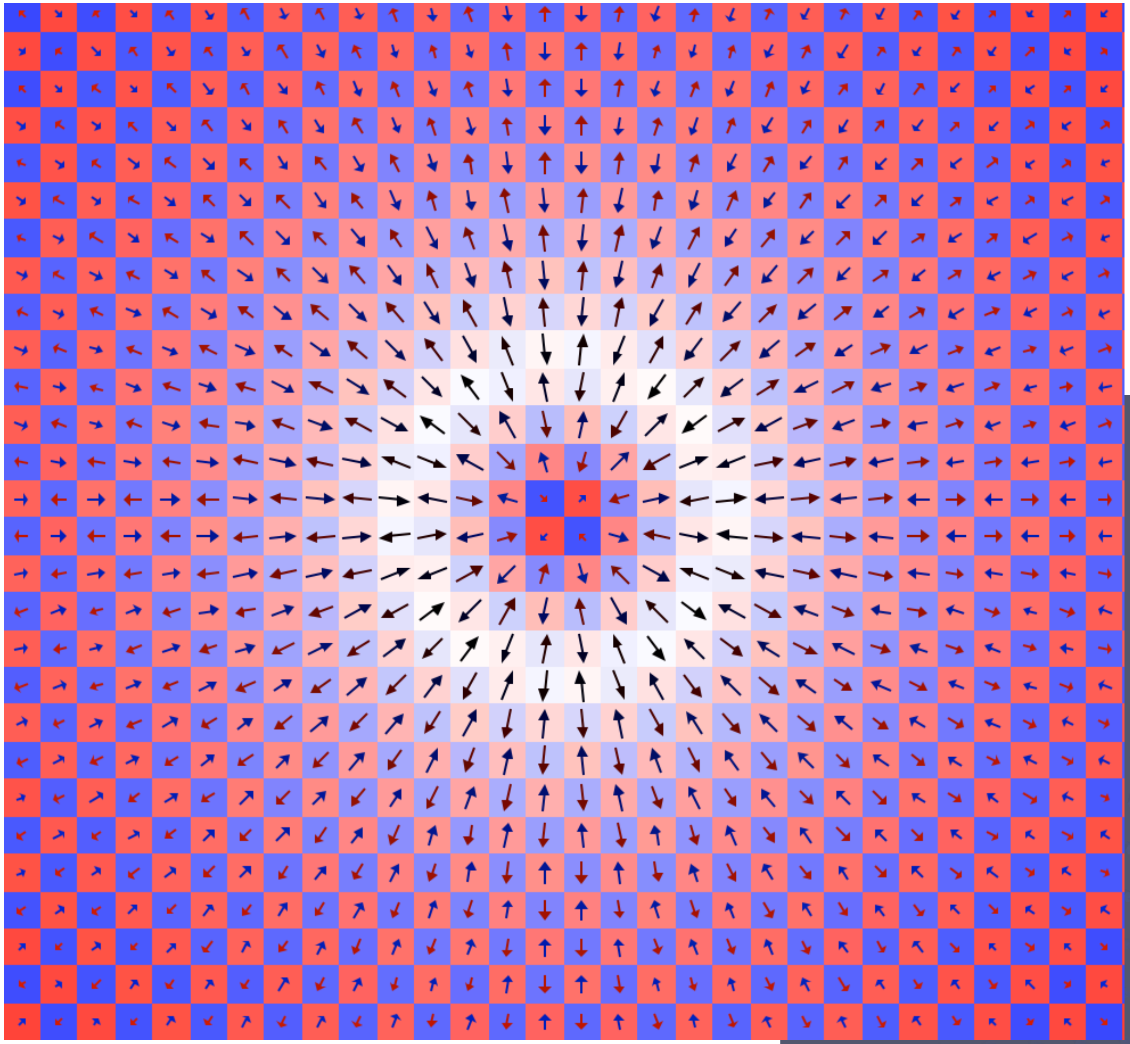


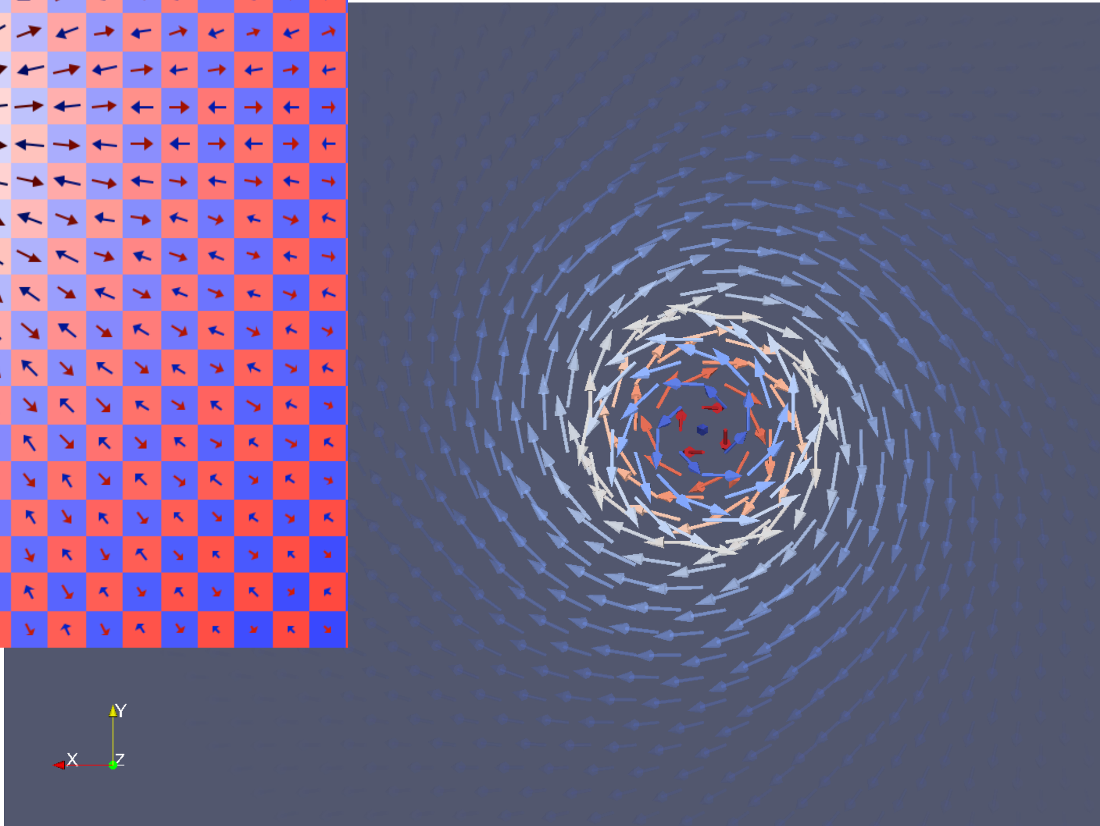
Winding number:

$$W = \frac{1}{4\pi}\int d^2r\,\Omega\cdot\frac{\partial\Omega}{\partial x}\times\frac{\partial\Omega}{\partial y}$$

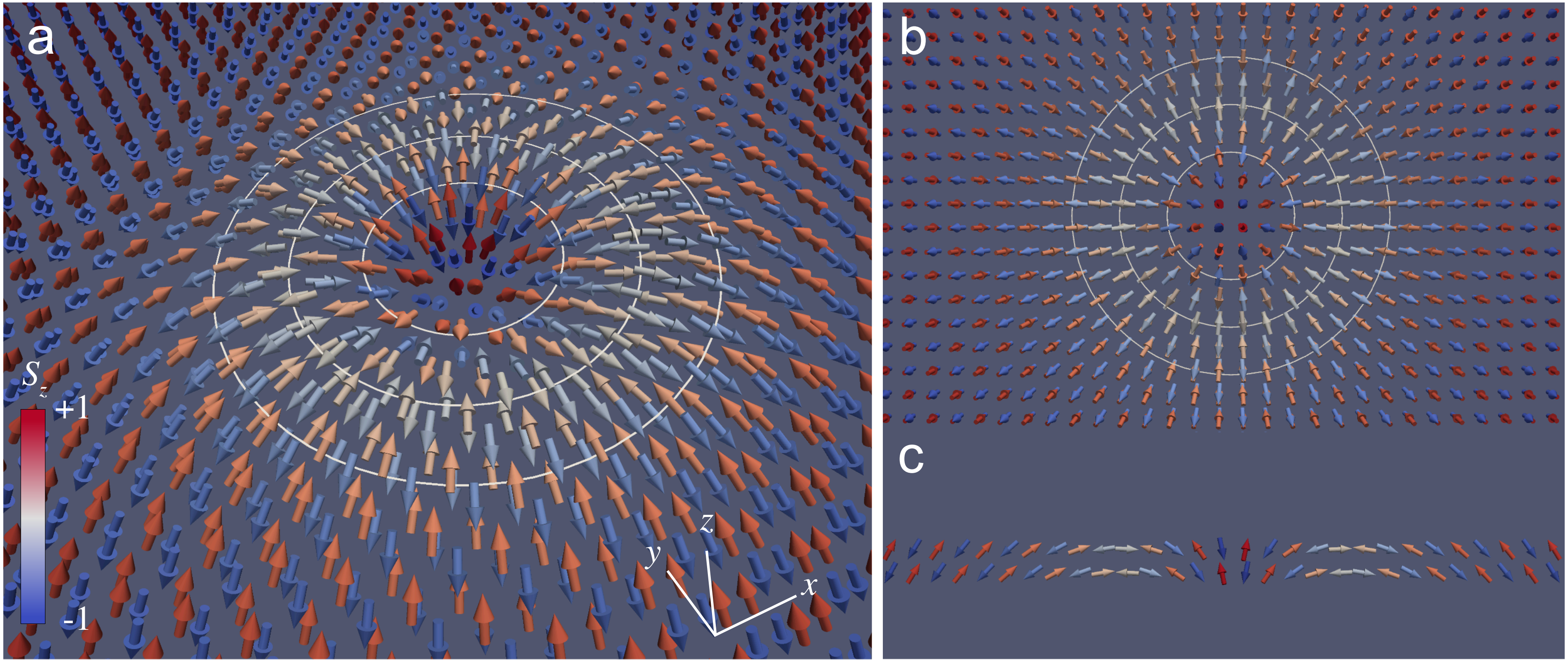


# Small AFM Skyrmion





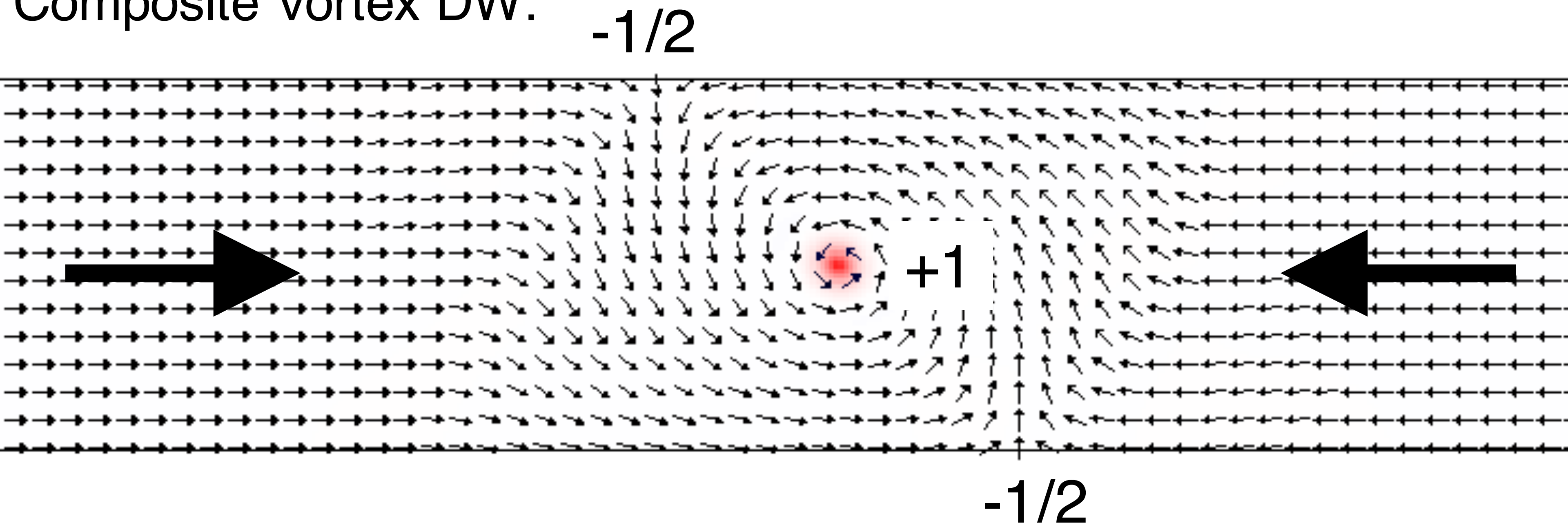
# AFM Skyrmion Structure



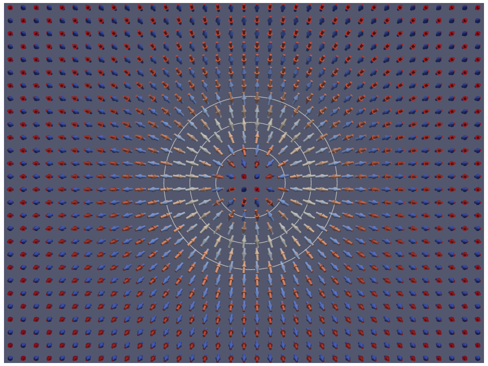

Winding number: $W = \frac{1}{4\pi} \int d^2r \, \Omega \cdot \frac{\partial \Omega}{\partial x} \times \frac{\partial \Omega}{\partial y}$

# Composite topological objects

Composite vortex DW:




AFM skyrmion:



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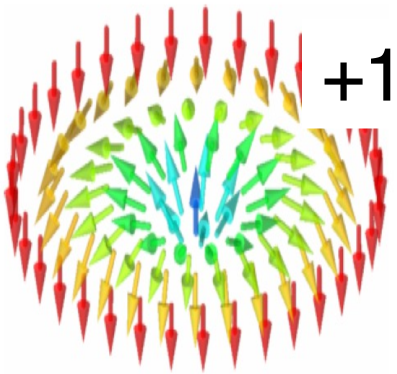


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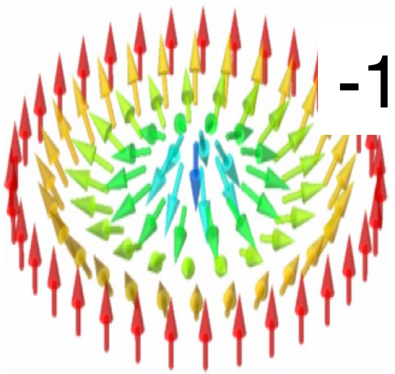
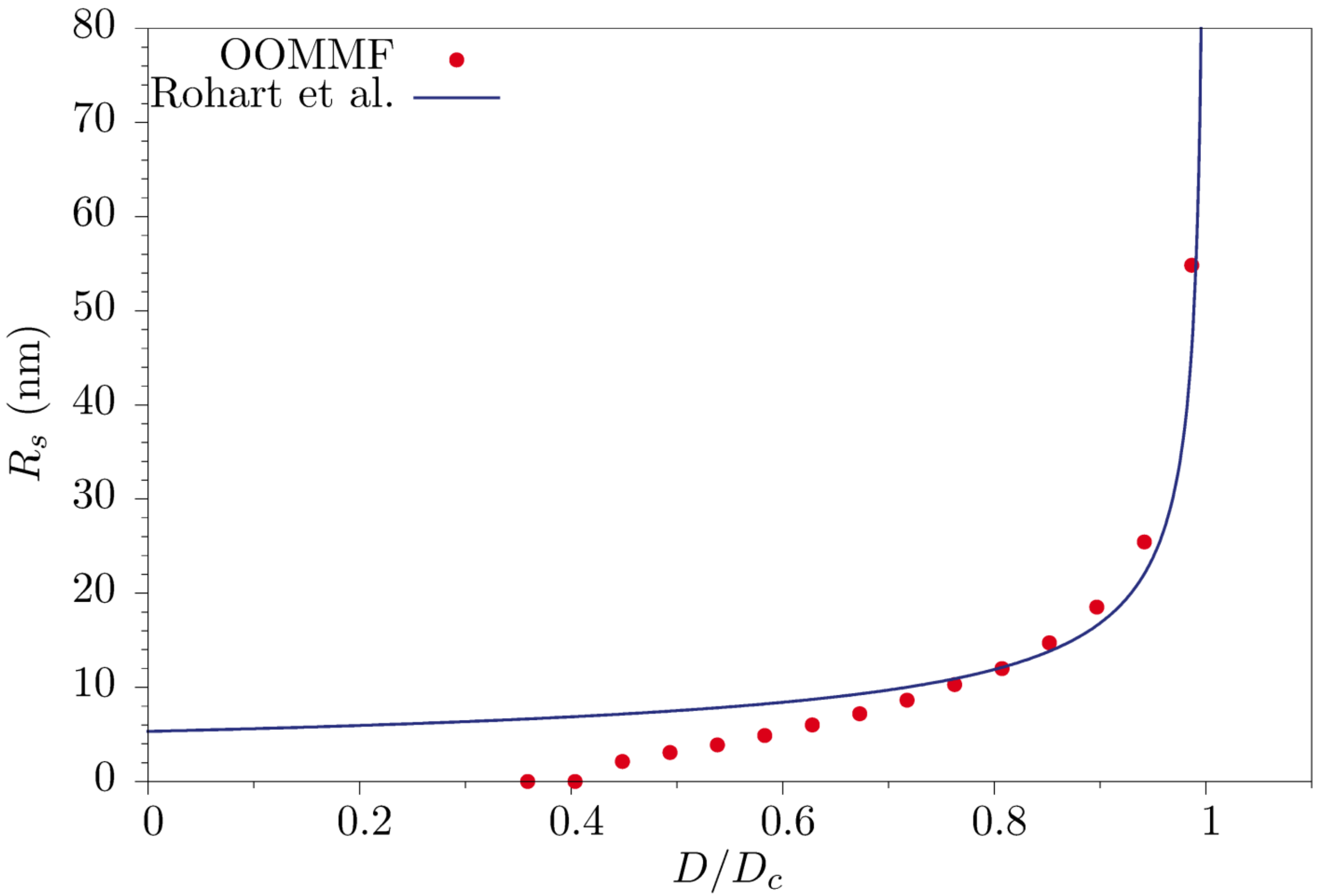



Total topological charge is zero.

# Skyrmion Radius vs. DMI

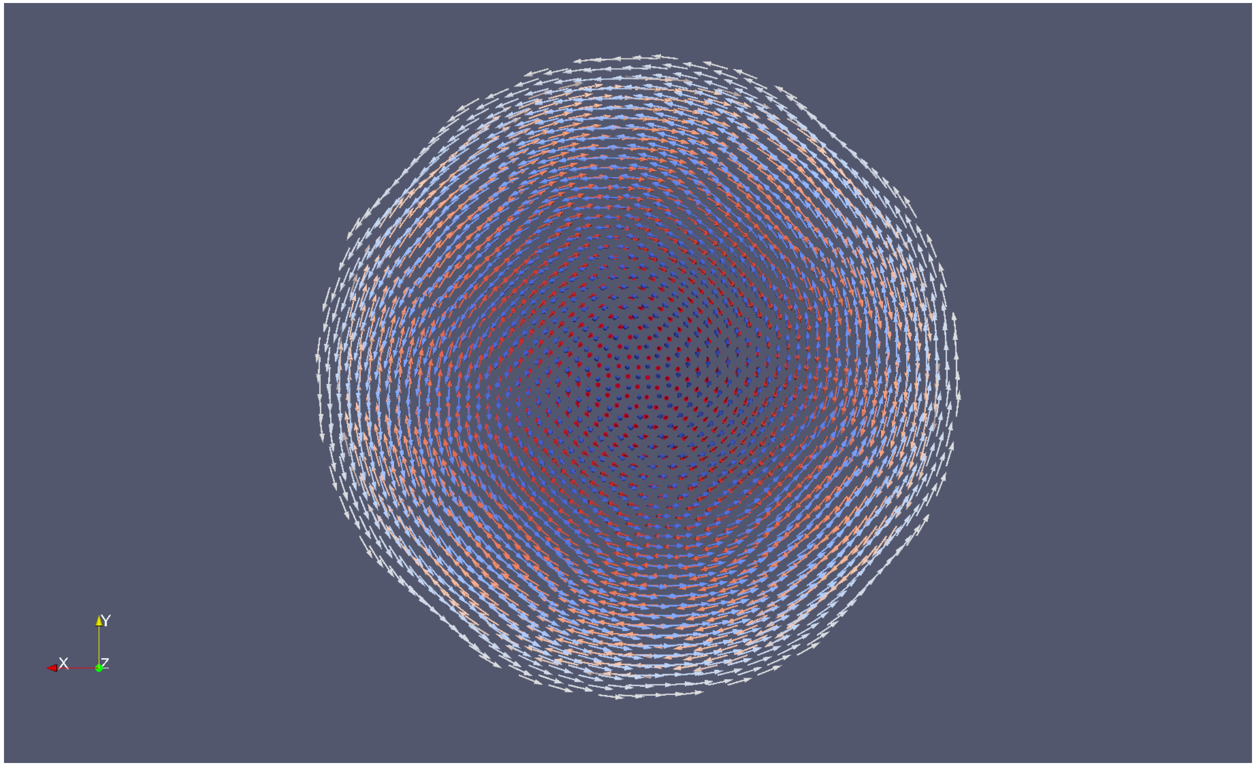



Rohart et.al, PRB (2013 )

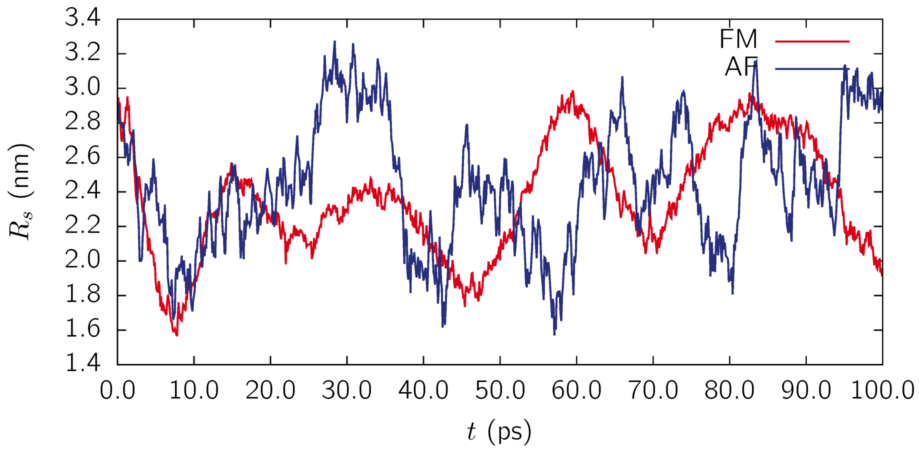
$$R_s \approx \frac{\Delta}{\sqrt{2(1 - D/D_c)}}$$

Large AFM/FM skyrmions described well by continuous model

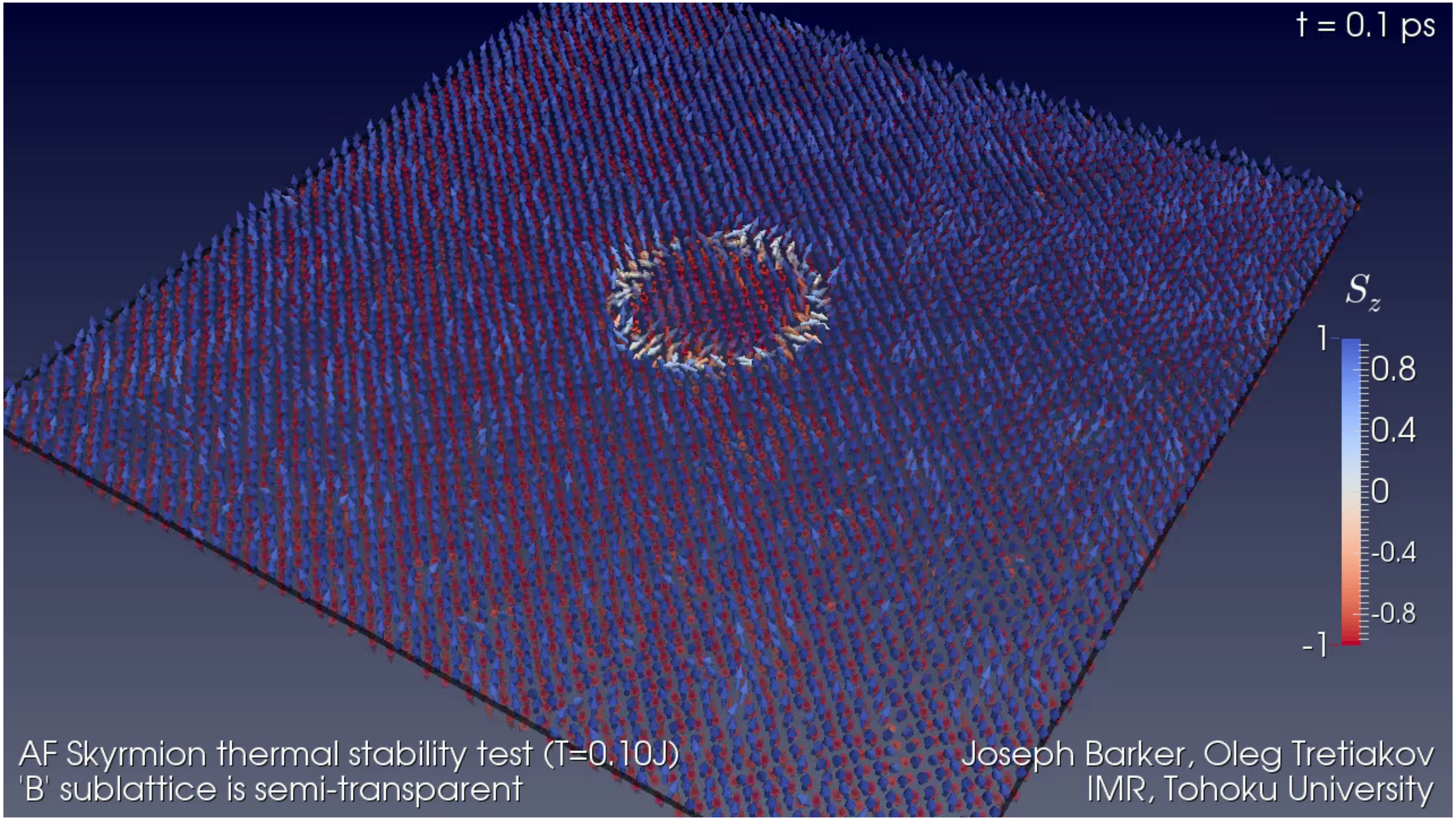
# AFM Skyrmion Structure at nonzero T




Temperature effects on AFM and FM Skyrmion radius:



# Temperature Effects on AFM Skyrmion



# Langevin LLG Approach

Landau-Lifshitz-Gilbert (LLG) equation:

$$\frac{\partial \vec{S}_i}{\partial t} = -\frac{\gamma_i}{(1+\alpha_i^2)}\left(\vec{S}_i \times \vec{H}_i + \alpha_i \vec{S}_i \times \vec{S}_i \times \vec{H}_i\right)$$

$$\vec{H}_i = -\frac{1}{\mu_s}\frac{\partial \mathcal{H}}{\partial \vec{S}_i} + \vec{\xi}_i$$

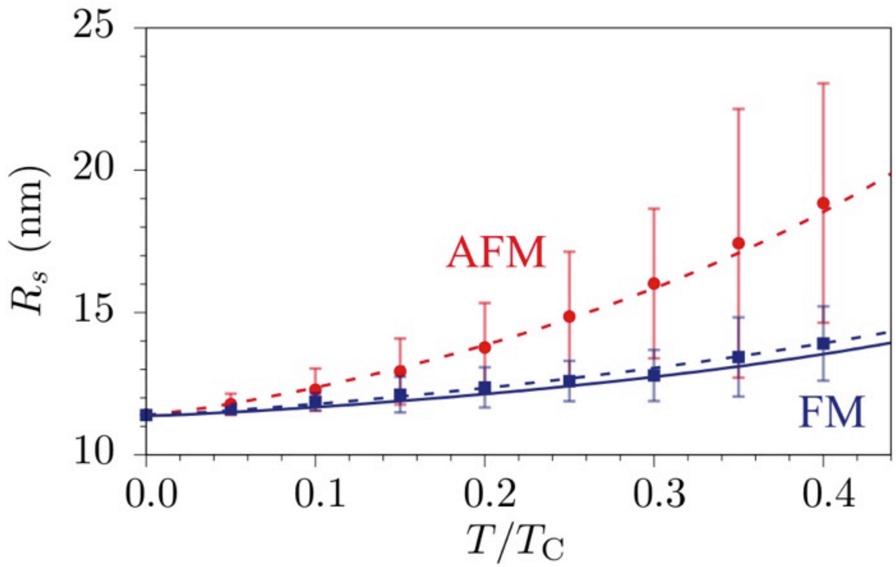
Stochastic process with the correlators:

$$\langle \vec{\xi}_i(t) \rangle = 0$$

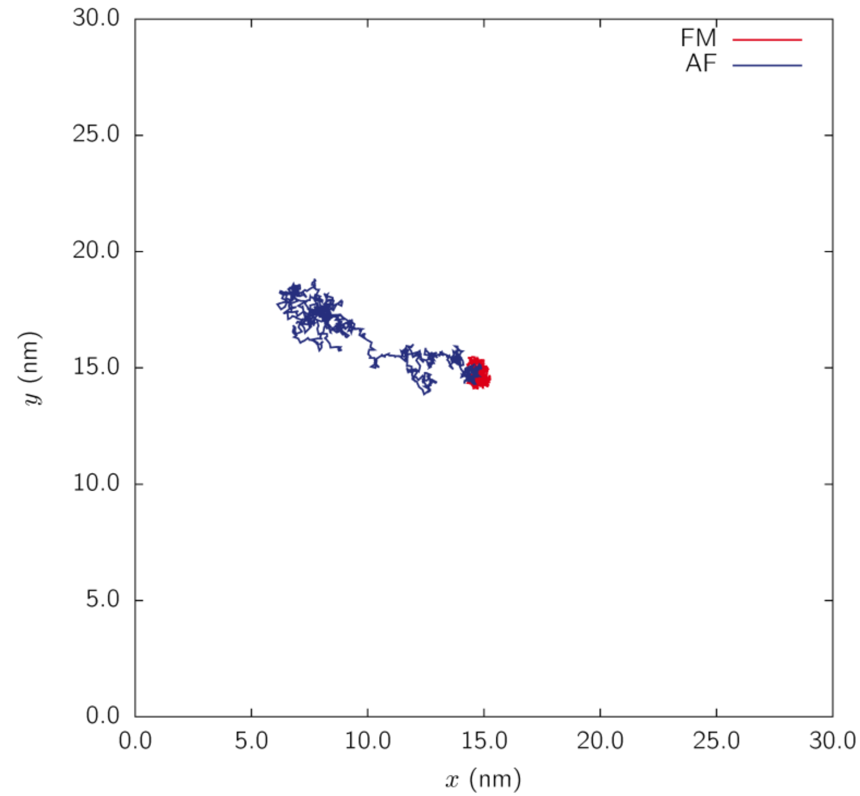
$$\langle \xi_{i,a}(t), \xi_{j,b}(t') \rangle = (2k_B T \alpha_i \mu_i / \gamma_i)\delta(|t-t'|)\delta_{ij}\delta_{ab}$$

# Thermal Effects on AFM Skyrmions

Skyrmion Radius vs. Temperature:



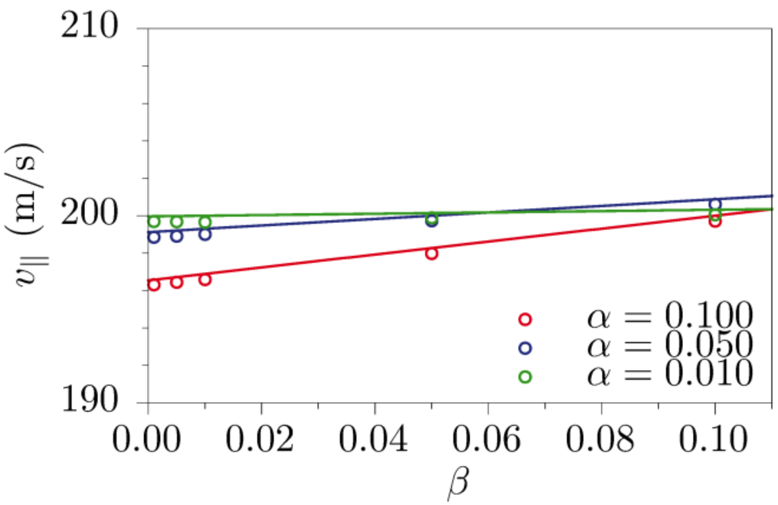

Random Thermal Walk of FM and AFM skyrmions:




AFM Skyrmions have higher diffusion coef.!

# Velocity along the Current

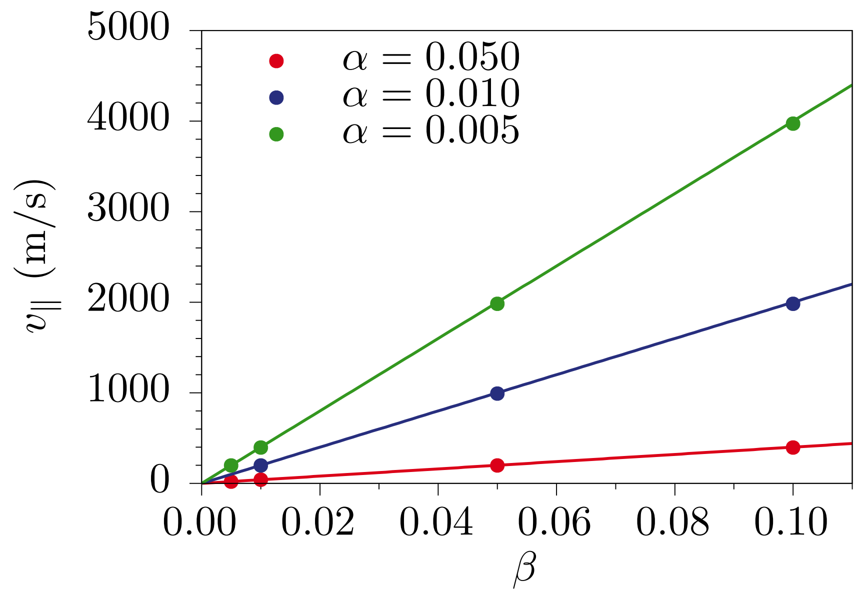
FM skyrmion longitudinal velocity:




$$v_{||} = \left( \frac{\beta}{\alpha} + \frac{\alpha - \beta}{\alpha^3 (D/G)^2 + \alpha} \right) j$$

$$j = \frac{P g \mu_B J}{2 e M_s}$$

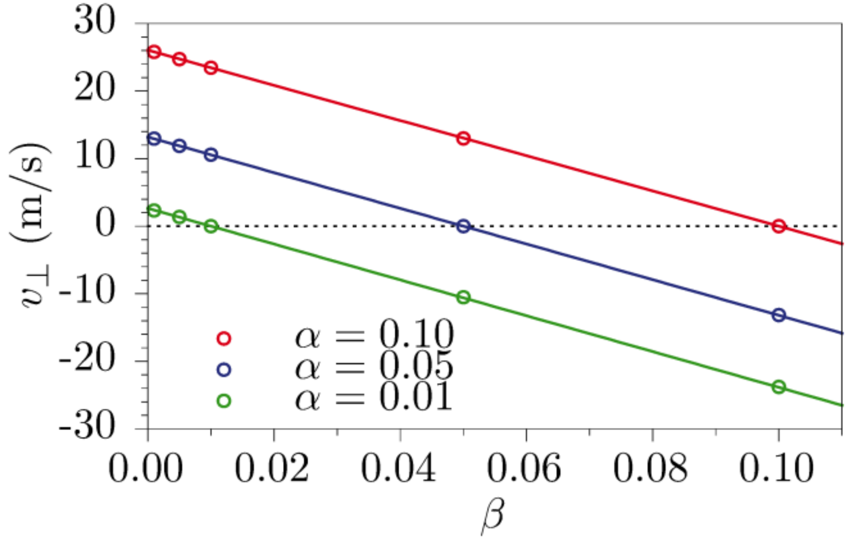
AFM skyrmion longitudinal velocity:




AFM skyrmions moved much faster by current!

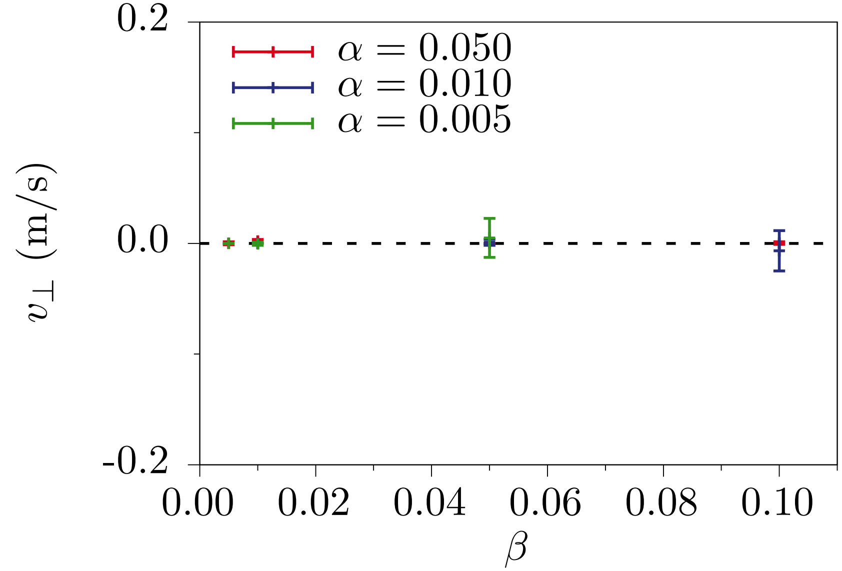
# Velocity transverse to the Current

FM skyrmion transverse velocity:



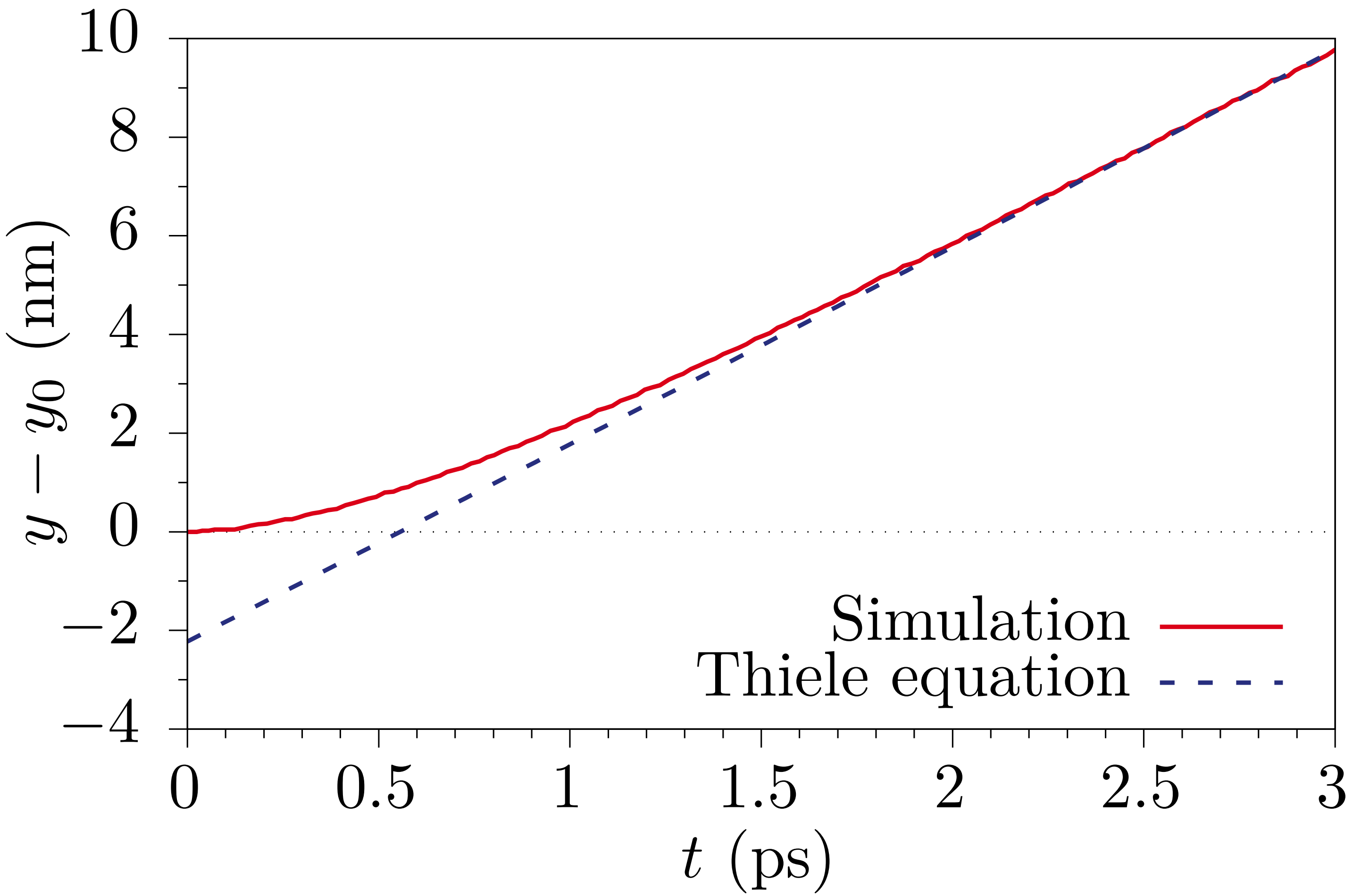

$$v_\perp = \frac{(\alpha - \beta) D/G}{1 + \alpha^2 (D/G)^2} \mathbf{z} \times \mathbf{j}$$

AFM skyrmion transverse velocity:




AFM skyrmion moves strictly along the current!

# AFM Skyrmion Dynamics




AFM skyrmion quickly (~2ps) reaches terminal velocity

# Current Induced Skyrmion Dynamics

Thiele's equation:

$$G \times (\mathbf{j} - \mathbf{v}) + \Gamma(\beta\mathbf{j} - \alpha\mathbf{v}) = 0$$

$G$ - Gyrocoupling vector

$\Gamma$ - Dissipative tensor

FM Skyrmion velocity is given by

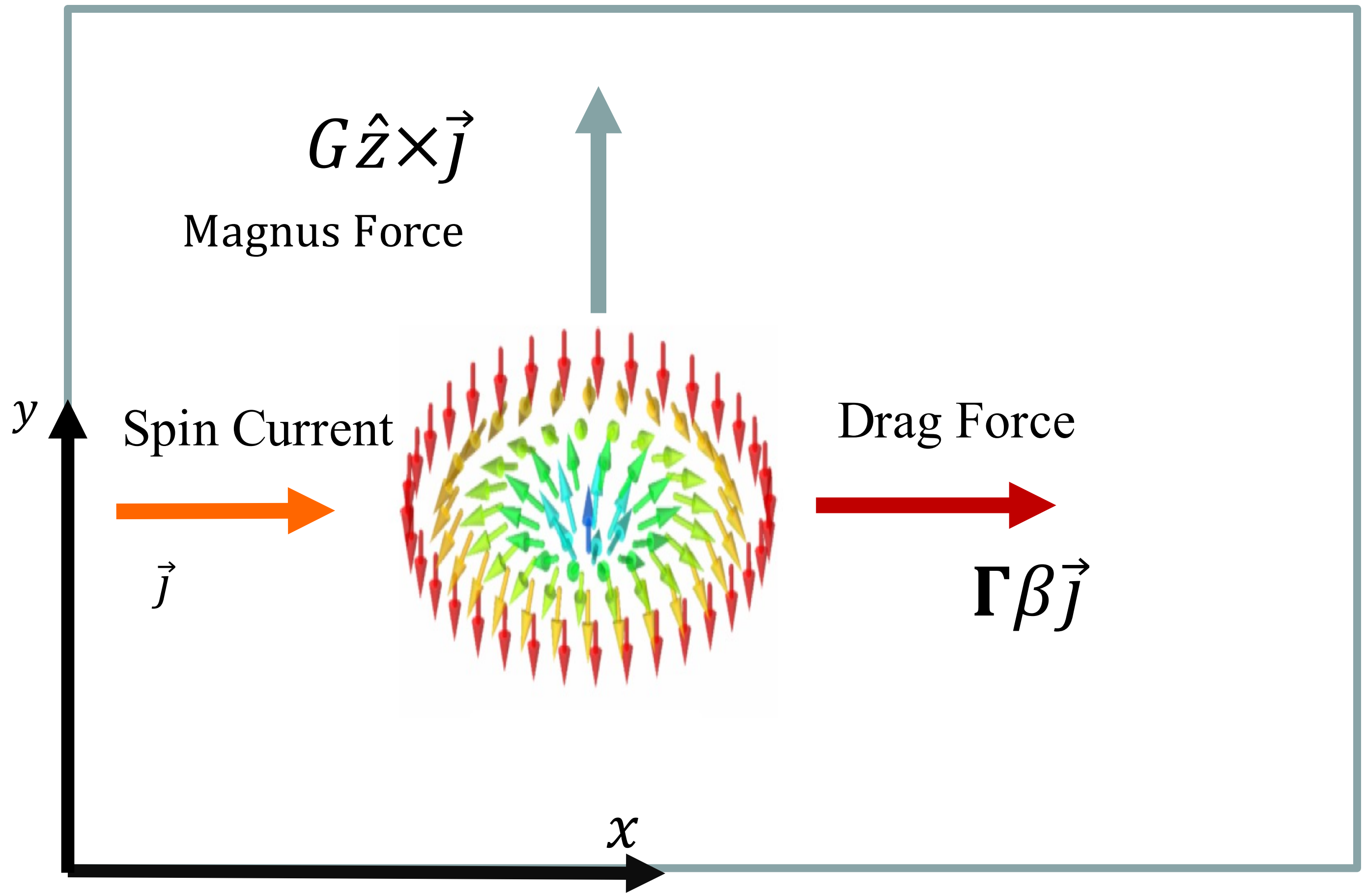
$$v_{||} = \left(\frac{\beta}{\alpha} + \frac{\alpha - \beta}{\alpha^3 (D/G)^2 + \alpha}\right) j$$

$$v_{\perp} = \frac{(\alpha - \beta) D/G}{1 + \alpha^2 (D/G)^2} \mathbf{z} \times \mathbf{j} \qquad \text{with } j = \frac{P g \mu_B J}{2 e M_s}$$

Shows the relation between current and velocity

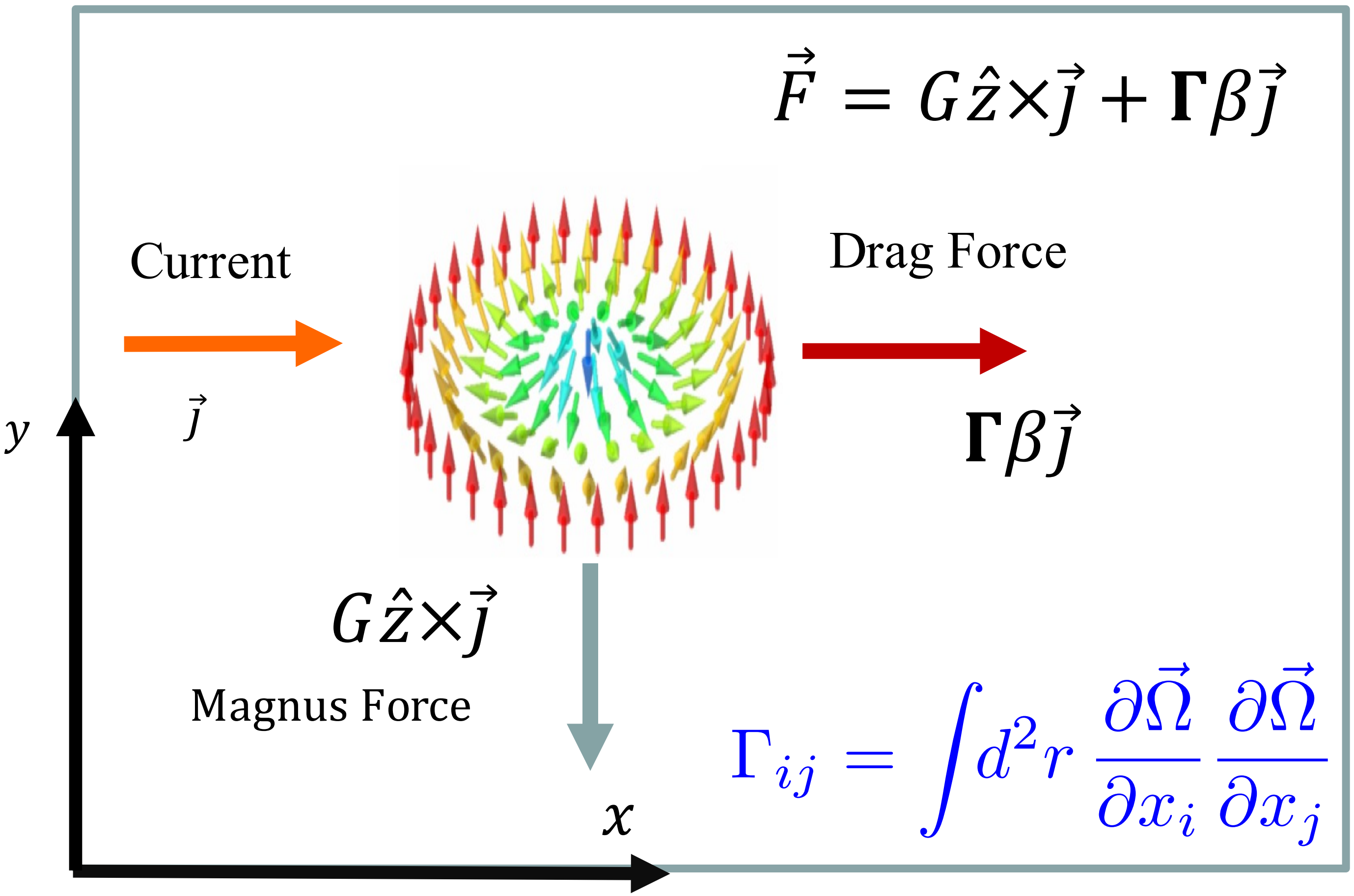
# FM Skyrmion Equation of Motion

Equation of motion for FM skyrmion: $G \times \mathbf{v}(t) + \Gamma\alpha\mathbf{v}(t) = \mathbf{F}$



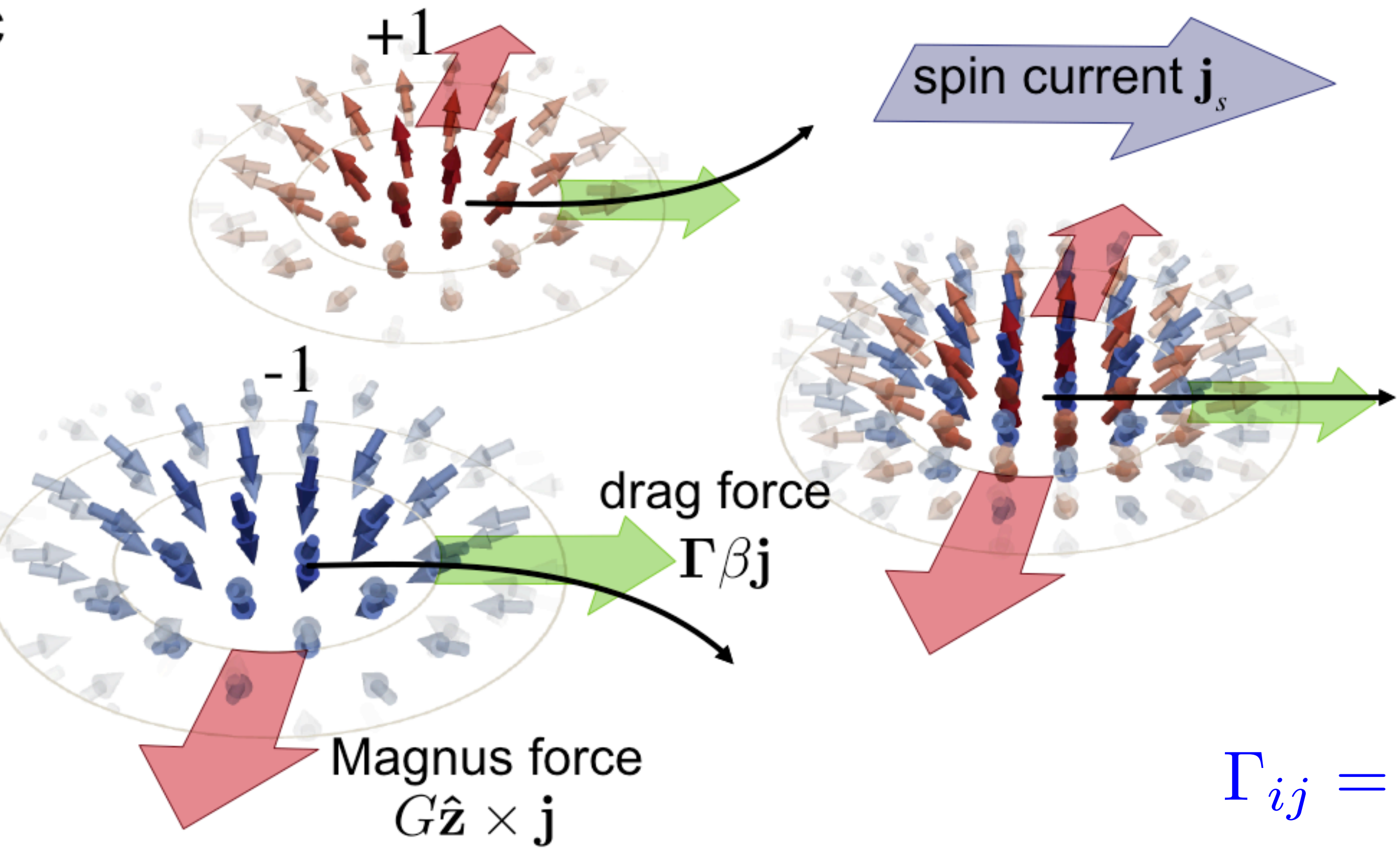
# AFM Skyrmion Equation of Motion

For the other sublattice of AFM skyrmion:




Equation of motion → $v_{||} = \frac{\beta}{\alpha} j$

# AFM Skyrmion Equation of Motion

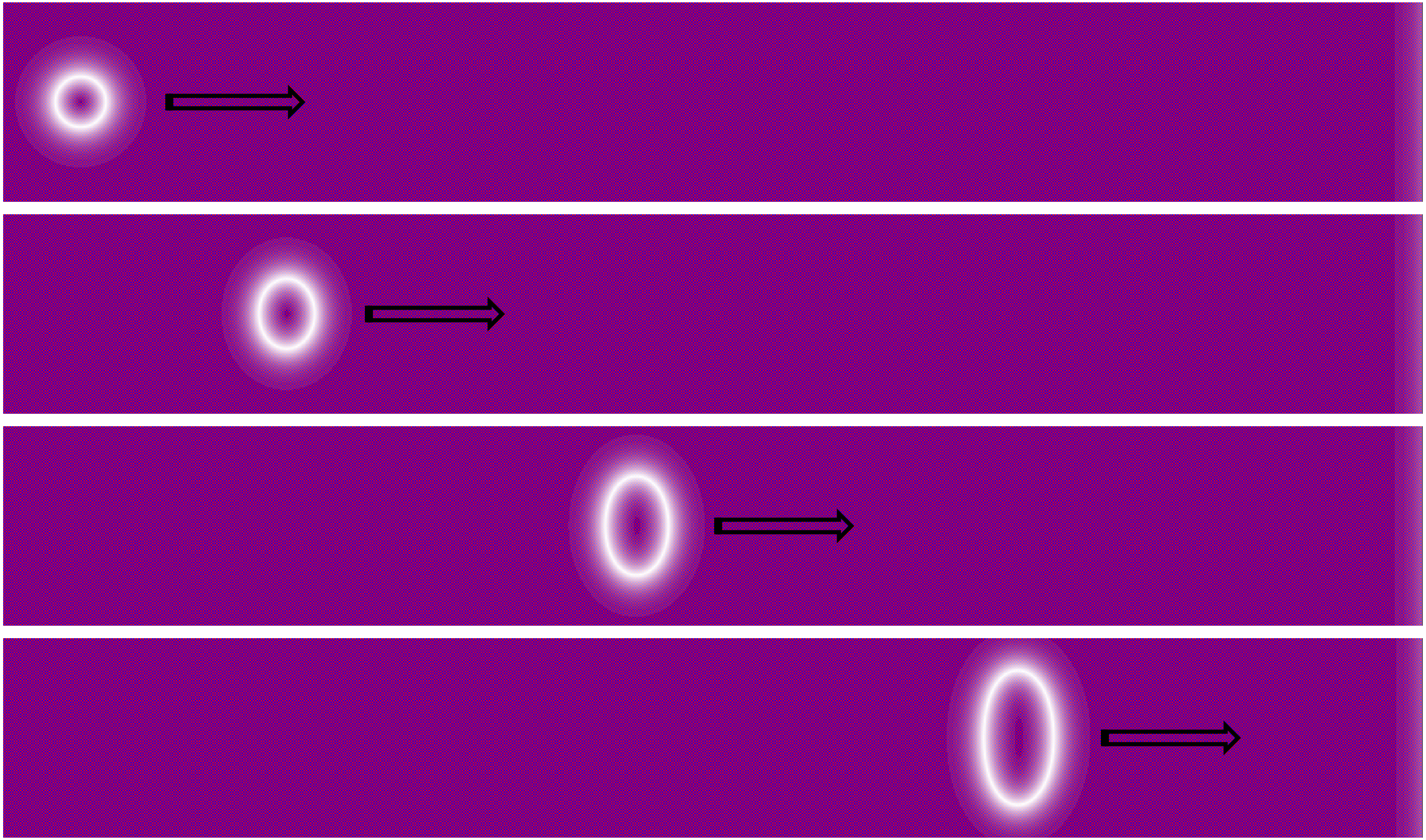



$$\alpha\Gamma\mathbf{v}(t) = \mathbf{F}$$

$$\Gamma_{ij} = \int d^2r \, \frac{\partial\vec{\Omega}}{\partial x_i}\frac{\partial\vec{\Omega}}{\partial x_j}$$

Equation of motion → $v_{||} = \dfrac{\beta}{\alpha} j$

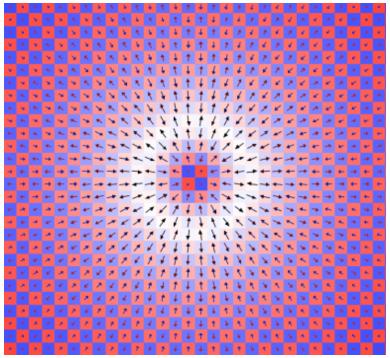
# Motion of Deformed AFM Skyrmion

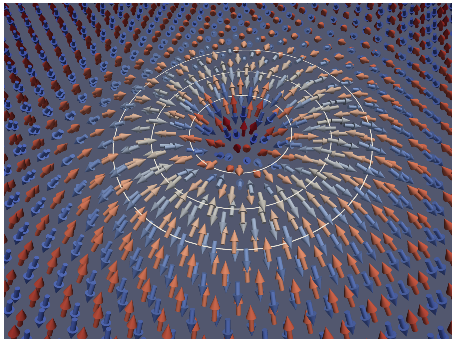


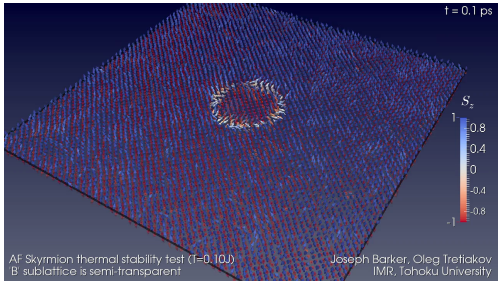
Big advantage: for high currents, even though skyrmion deforms – it still moves strictly parallel to the current!

# Summary

- AFM skyrmions are stable objects. The effect of ***Dzyaloshinskii-Moriya interaction*** on the AFM skyrmion stability/radius were studied.
- Thermal effects on AFM skyrmions were studied. Diffusion constant for AFM skyrmions is larger than for FM skyrmions.
- Skyrmion dynamics in AFMs obeys ***generalized Thiele's equations for AFMs***.
- *AFM skyrmions move only* ***along the currrent***.





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