Effects of disorder on magnetic vortex dynamics

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Effects of disorder and internal dynamics on vortex wall propagation
Hongki Min, Robert D. McMichael, Michael J. Donahue, Jacques Miltat, and M. D. Stiles
Phys. Rev. Lett. **104**, 217201 (2010)

Effects of disorder on magnetic vortex gyration
Hongki Min, Robert D. McMichael, Jacques Miltat, and M. D. Stiles
Phys. Rev. B **83**, 064411 (2011)

Outline

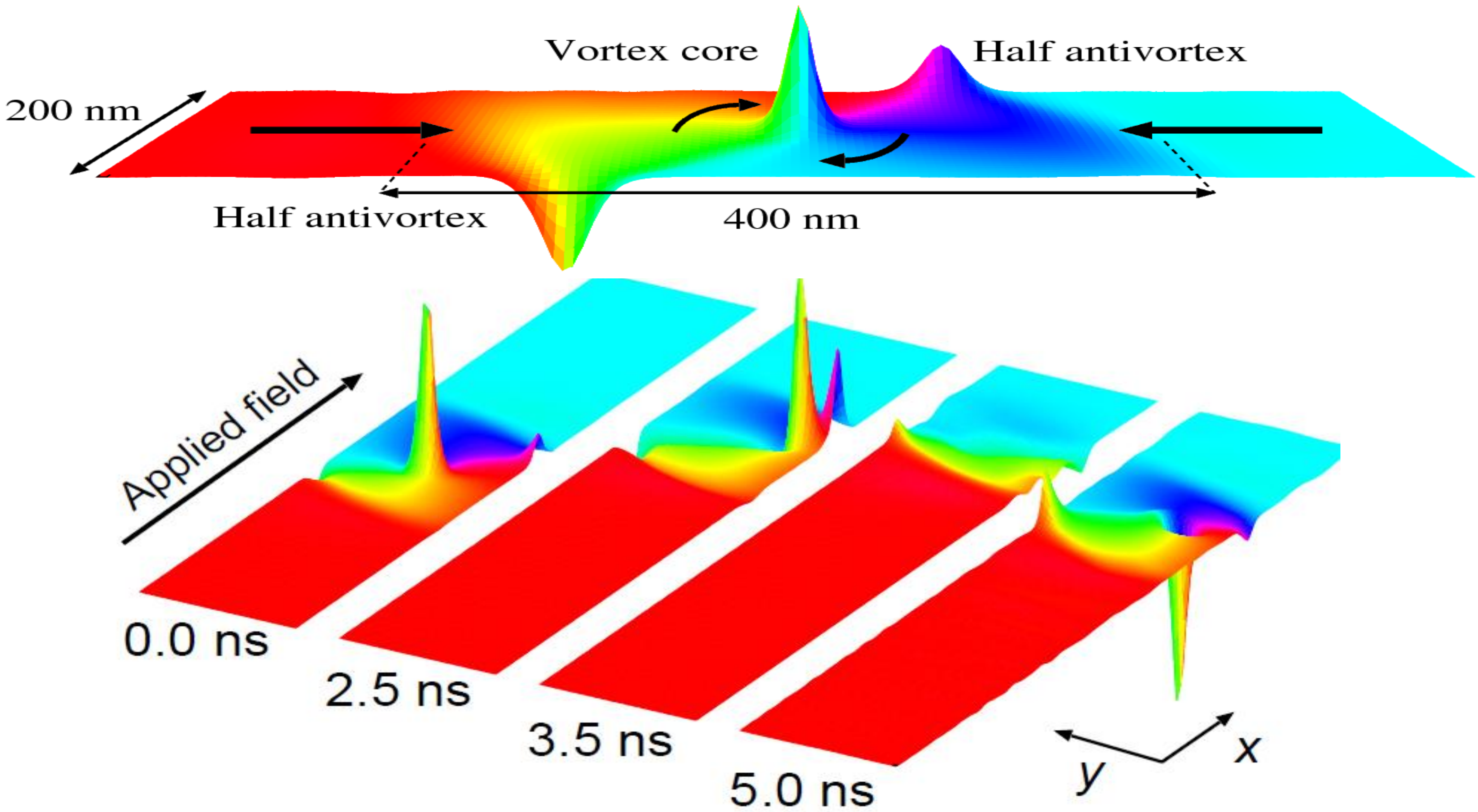
I. Effects of disorder on vortex wall propagation
   - Field-induced propagation
   - Current-induced propagation
   - Enhanced damping and internal dynamics

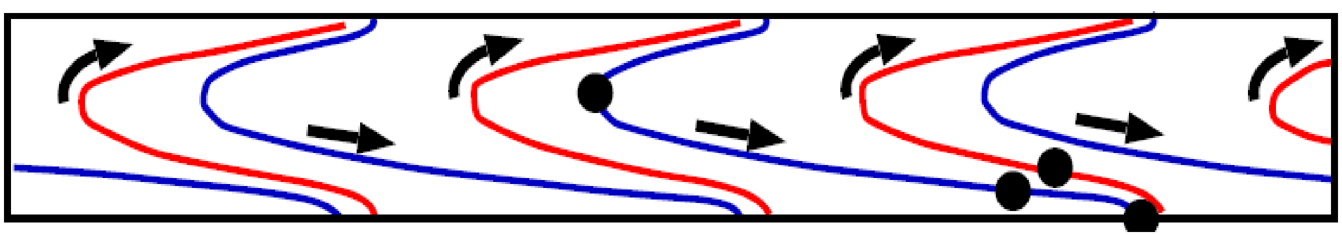
II. Effects of disorder on vortex gyration
   - Gyration in a disordered film
   - Gyration in a single pinning potential

Extrinsic disorder and excitation of internal domain wall structures enhance the effective damping.

Motivation

Domain wall structure





Applied field

Field induced domain wall motion

Magnetization dynamics

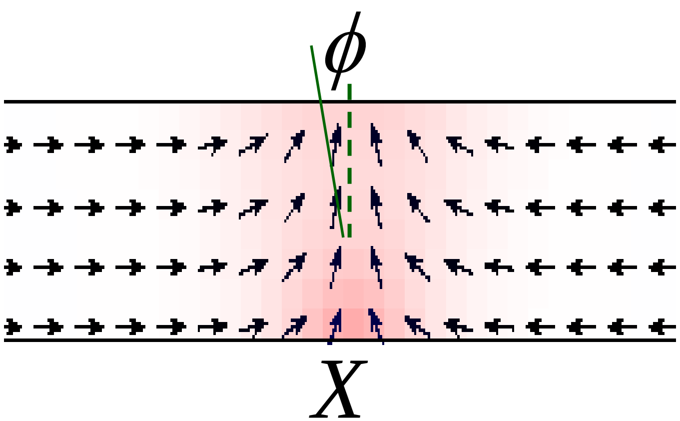
- Landau-Lifshits-Gilbert (LLG) equation

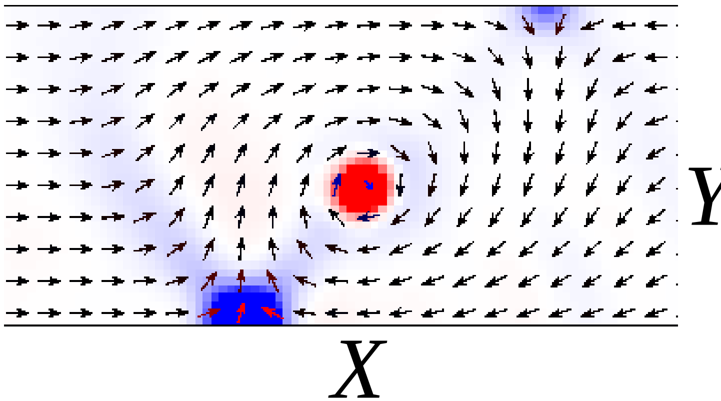
$$\boxed{\frac{\partial}{\partial t}\mathbf{M} = -\gamma \mathbf{M} \times \mathbf{H}_{\text{eff}} + \frac{\alpha}{M}\mathbf{M} \times \frac{\partial}{\partial t}\mathbf{M}}$$

$\mathbf{M}$ = magnetization γ = gyromagnetic ratio $\mathbf{H}_{\text{eff}}$ = Effective magnetic field α = Gilbert damping

Collective coordinate approach

- Transverse wall and vortex wall





Collective coordinate approach

Two-coordinate model for vortex core position

- Equations of motion $\boxed{(X,Y)}$

$$\boxed{\alpha \mathbf{D}\mathbf{V} = \mathbf{F} + \mathbf{V} \times \mathbf{G}}$$

$$m\dot{\mathbf{v}} + \Gamma \mathbf{v} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B})$$

$\mathbf{V} =$ time derivative of (X,Y)
$\mathbf{D} =$ viscosity tensor
$\mathbf{F} =$ generalized force
$\mathbf{G} =$ gyroscopic tensor
$\alpha =$ Gilbert damping

$$D_{ij} = \int dx^3 \frac{\partial \mathbf{m}}{\partial X_i} \cdot \frac{\partial \mathbf{m}}{\partial X_j}$$

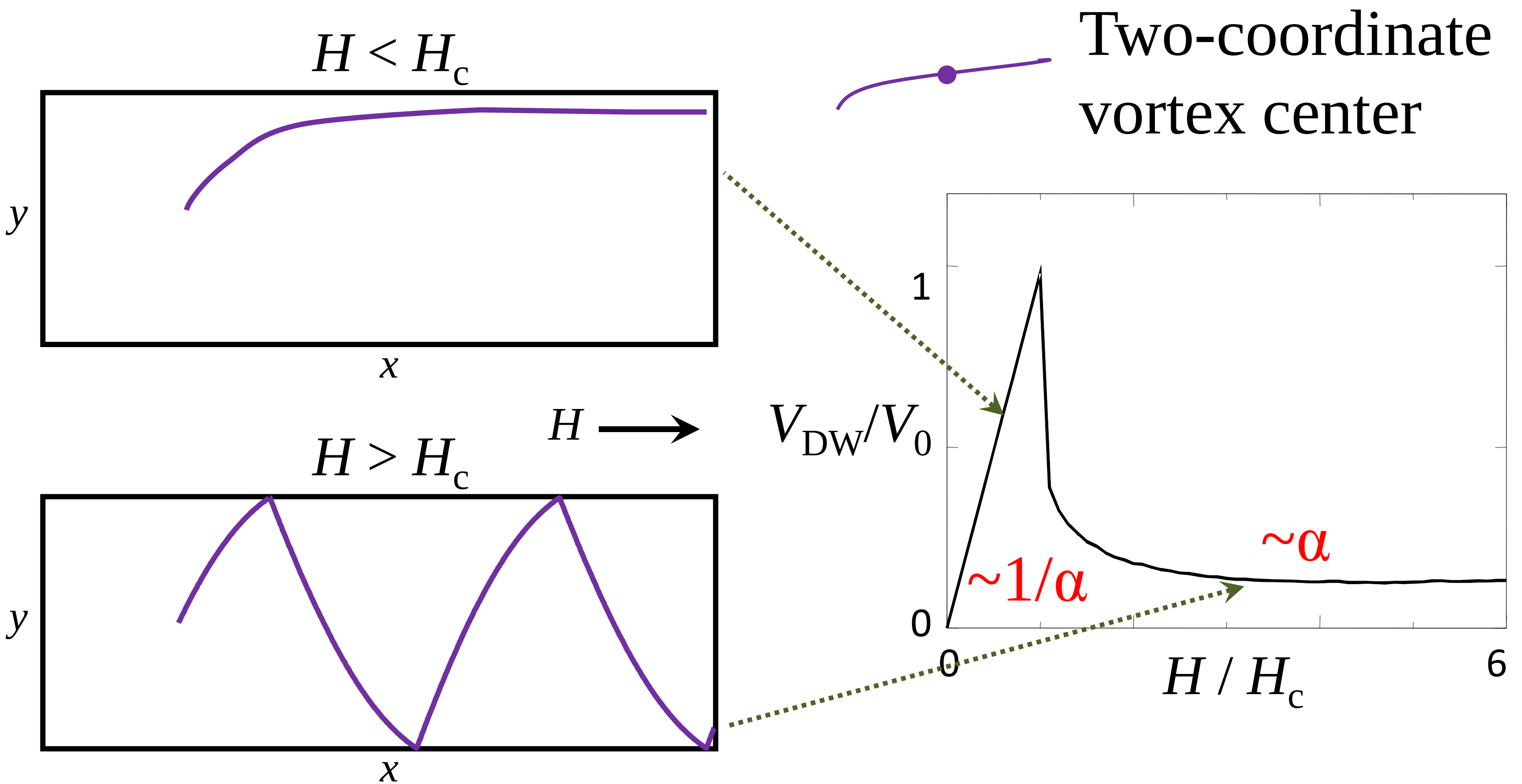
$$F_i = \gamma \int dx^3 \mathbf{H}_{\text{eff}} \cdot \frac{\partial \mathbf{m}}{\partial X_i} = -\frac{\gamma}{\mu_0 M} \frac{\partial E}{\partial X_i}$$

$$G_{ij} = \int dx^3 \mathbf{m} \cdot \left(\frac{\partial \mathbf{m}}{\partial X_i} \times \frac{\partial \mathbf{m}}{\partial X_j} \right)$$

Thiele, PRL **30**, 230 (1973);
Schryer and Walker, JAP **45**, 5406 (1974);
Thiaville *et al*, EPL **69**, 990 (2005);
Li and Zhang, PRB **70**, 024417 (2004);
He *et al*, PRB **73**, 184408 (2006);
Tretiakov *et al*, PRL **100**, 127204 (2008);
Clarke *et al*, PRB **78**, 134412 (2008);
…..

2D massless charged particle moving through a medium with a viscosity tensor $\alpha\mathbf{D}$ in the presence of an in-plane electric field $\mathbf{F}$ and a perpendicular magnetic field $\mathbf{G}$

Collective coordinate approach



Does this reduced model, which ignores the extrinsic disorder and internal structure of the domain wall, provide a good interpretation of experiments?

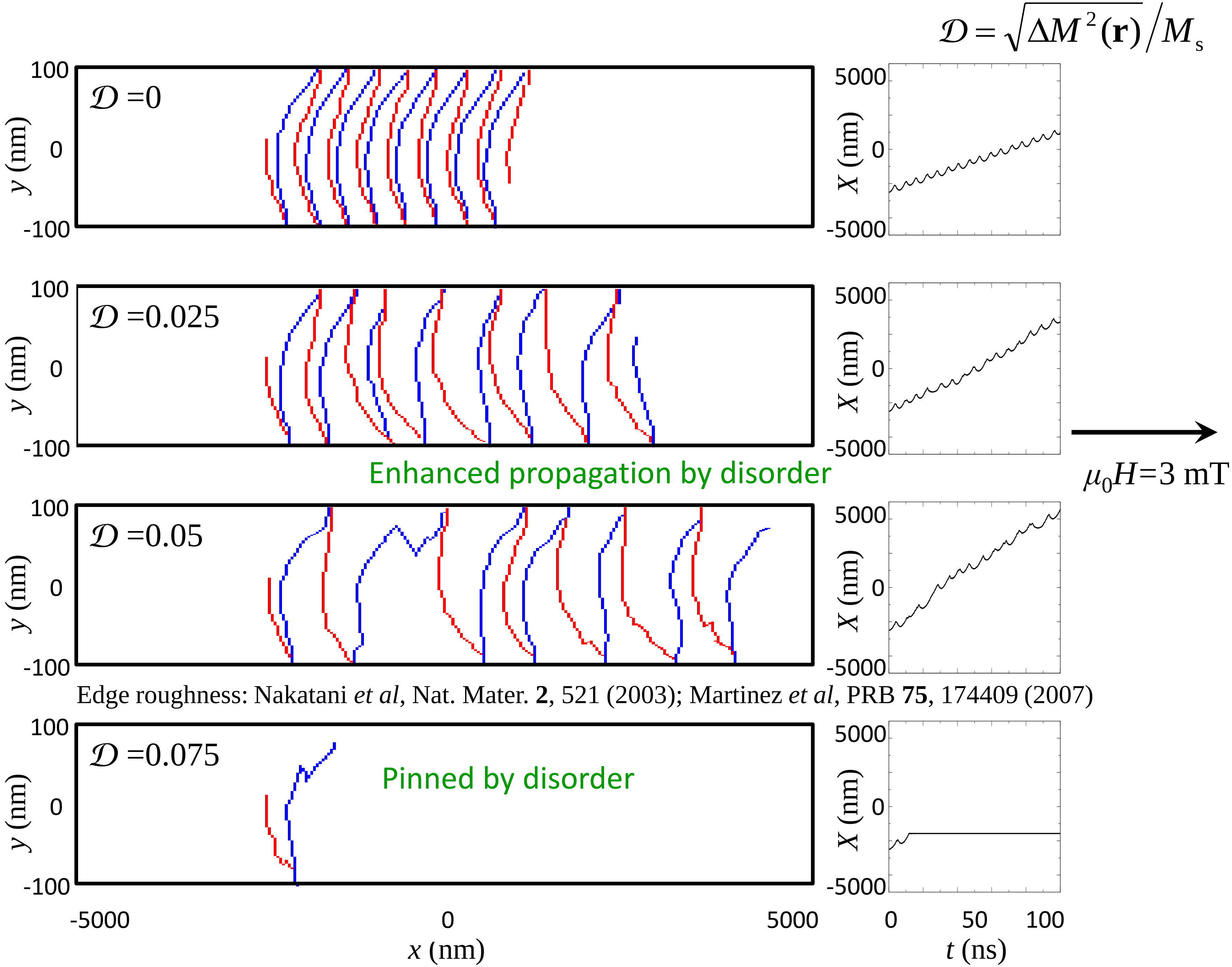
Simulation

- LLG equation solver
  - Objected Oriented MicroMagnetic Framework
- Permalloy ($Ni_{80}Fe_{20}$) thin film
  - 200 nm width, 20 nm thickness, 5 nm cell size
  - 10000 nm ~ 15000 nm length
- Disorder model
  - Correlated variation in M_s to model thickness fluctuations

$$\mathcal{D} = \frac{\sqrt{\langle M(\mathbf{r}) - M_s \rangle^2}}{M_s}$$

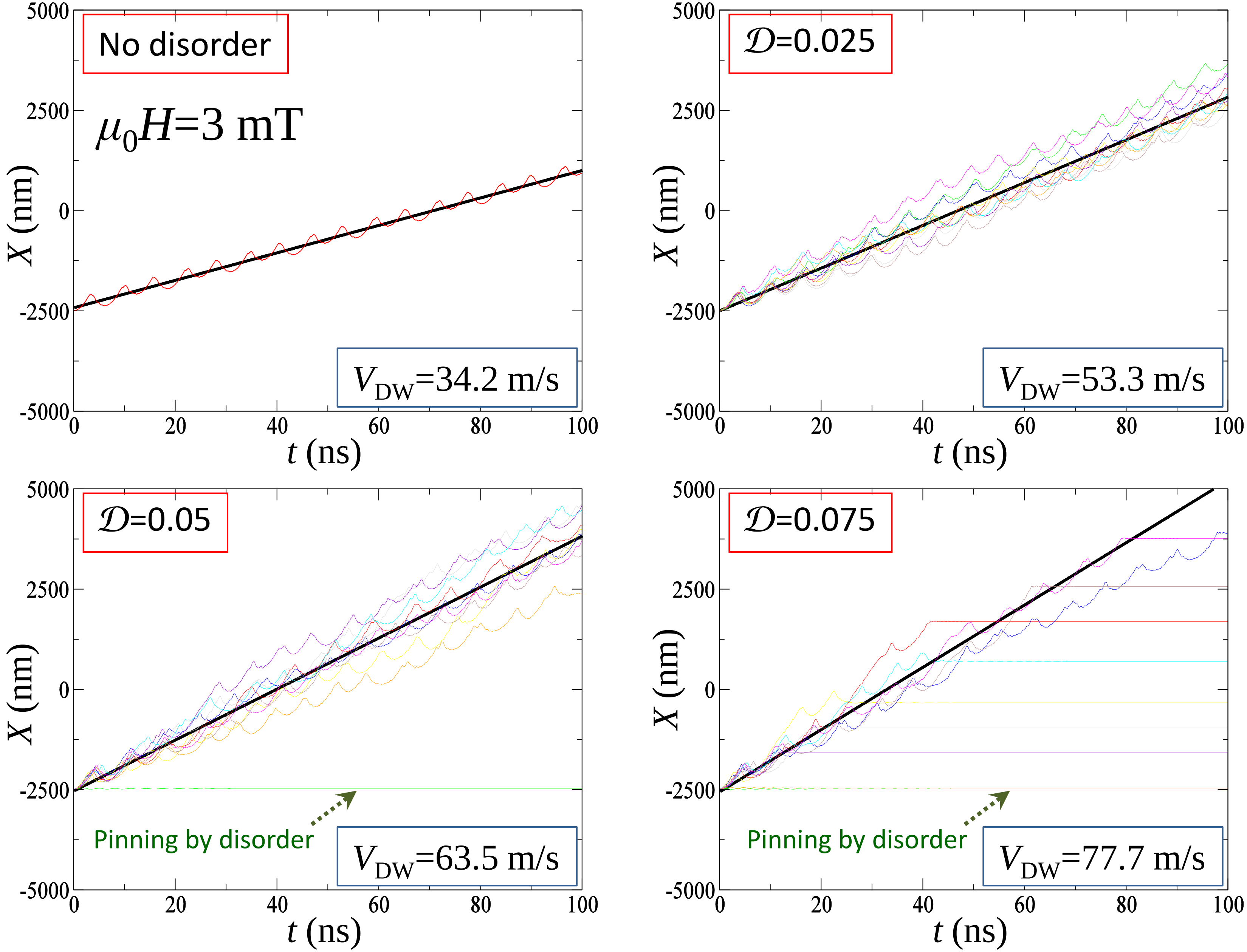
- Removing finite size effects

  - Compensating fields at ends
  - Absorbing boundary conditions at ends



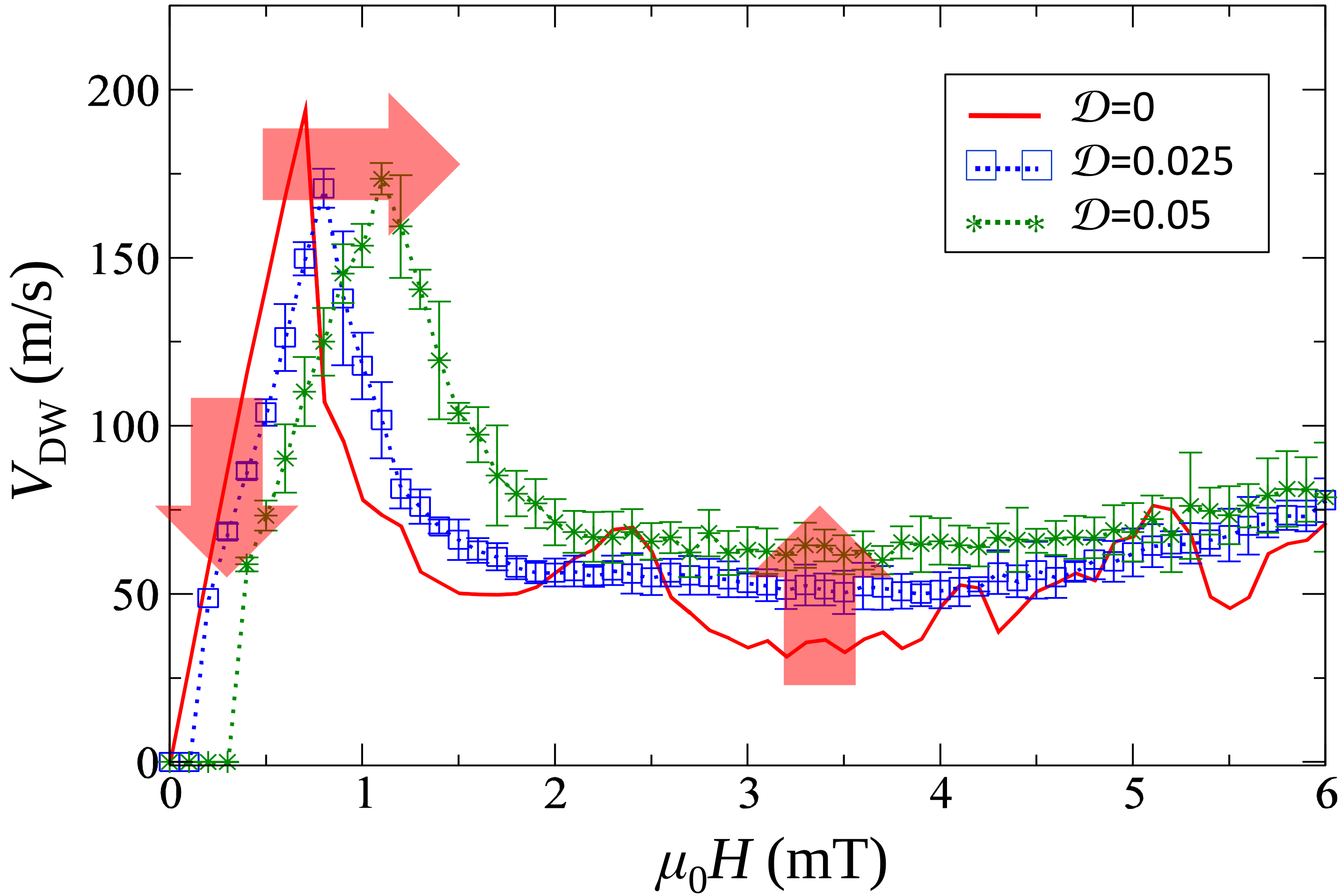
$\mathcal{D} = \sqrt{\Delta M^2(\mathbf{r})} / M_s$
$\mathcal{D}$ =0
$\mathcal{D}$ =0.025
$\mathcal{D}$ =0.05
$\mathcal{D}$ =0.075
Enhanced propagation by disorder
Pinned by disorder
$\mu_0 H$=3 mT
Edge roughness: Nakatani *et al*, Nat. Mater. **2**, 521 (2003); Martinez *et al*, PRB **75**, 174409 (2007)
y (nm)
100
0
-100
x (nm)
-5000
0
5000
X (nm)
t (ns)
50
100

Velocity estimation by ensemble average



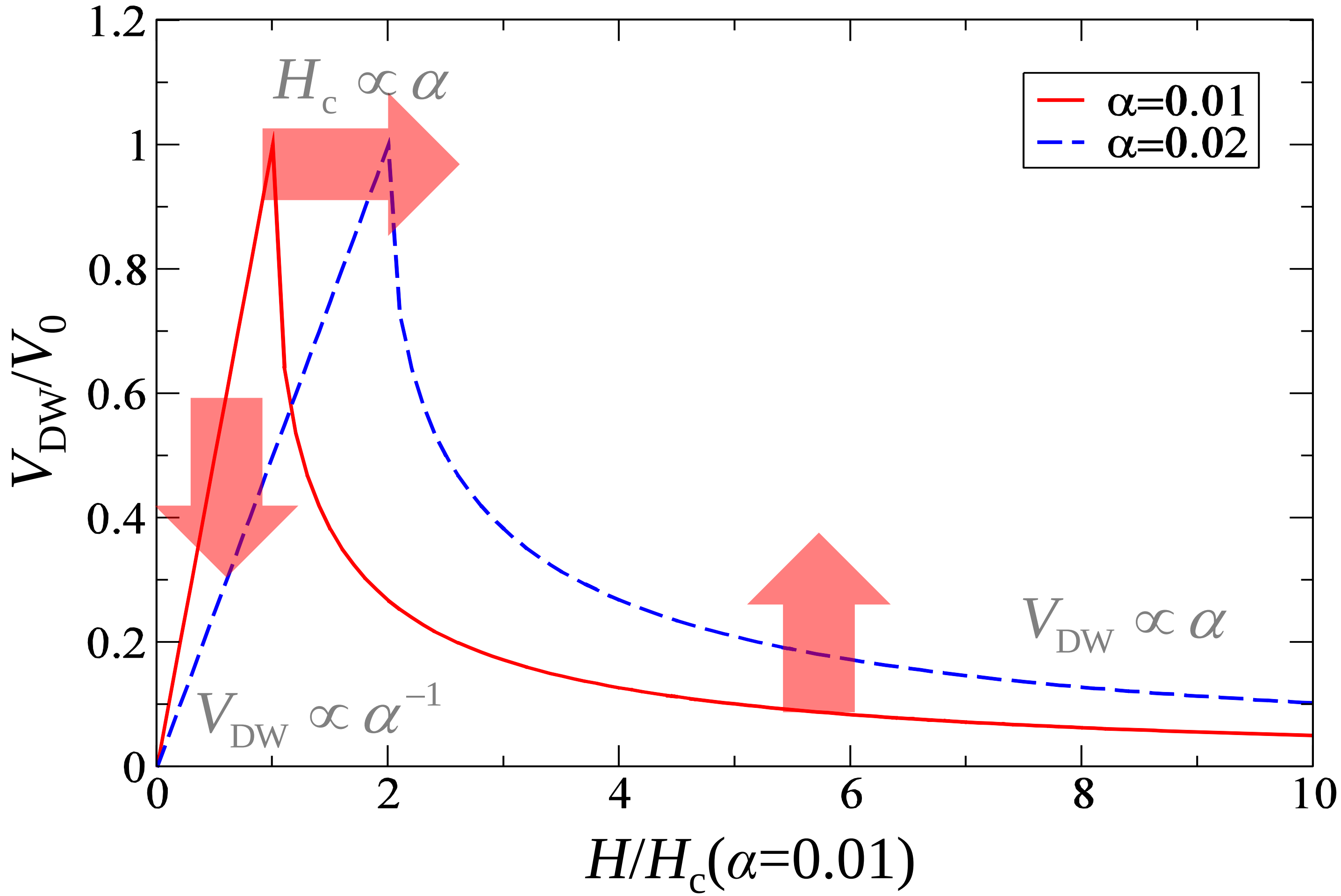
Disorder can enhance/suppress velocity

Domain wall velocity as a function of field



Ideal model with different damping constants

Domain wall velocity as a function of fields



Results can be understood in terms of an effective damping that increases with the disorder.

Current induced domain wall motion

Magnetization dynamics

- Landau-Lifshits-Gilbert (LLG) equation

$$\left(\frac{\partial}{\partial t}+\mathbf{v}_{\mathrm{s}}\cdot\nabla\right)\mathbf{M}=-\gamma\mathbf{M}\times\mathbf{H}_{\mathrm{eff}}+\frac{\alpha}{M}\mathbf{M}\times\left(\frac{\partial}{\partial t}+\frac{\beta}{\alpha}\mathbf{v}_{\mathrm{s}}\cdot\nabla\right)\mathbf{M}$$

$\mathbf{M}$ = magnetization $\mathbf{H}_{\mathrm{eff}}$ = Effective magnetic field γ = gyromagnetic ratio

α = Gilbert damping β = spin-transfer torque parameter $\mathbf{v}_{\mathrm{s}}$ = spin velocity

Collective coordinate approach: Vortex wall

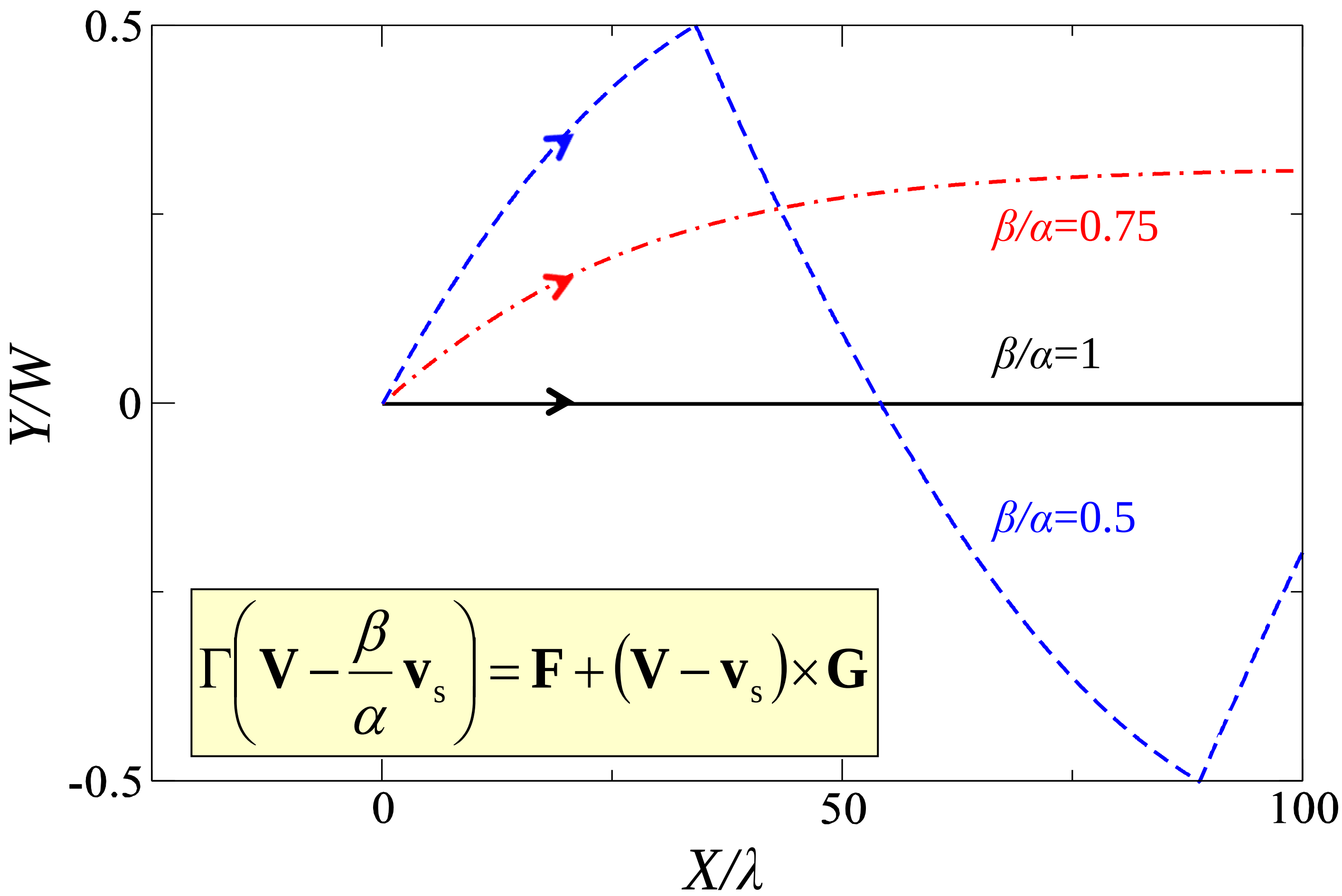
- Equations of motion $\boxed{(X, Y)}$

$$\Gamma\left(\mathbf{V}-\frac{\beta}{\alpha}\mathbf{v}_{\mathrm{s}}\right)=\mathbf{F}+\left(\mathbf{V}-\mathbf{v}_{\mathrm{s}}\right)\times\mathbf{G}$$

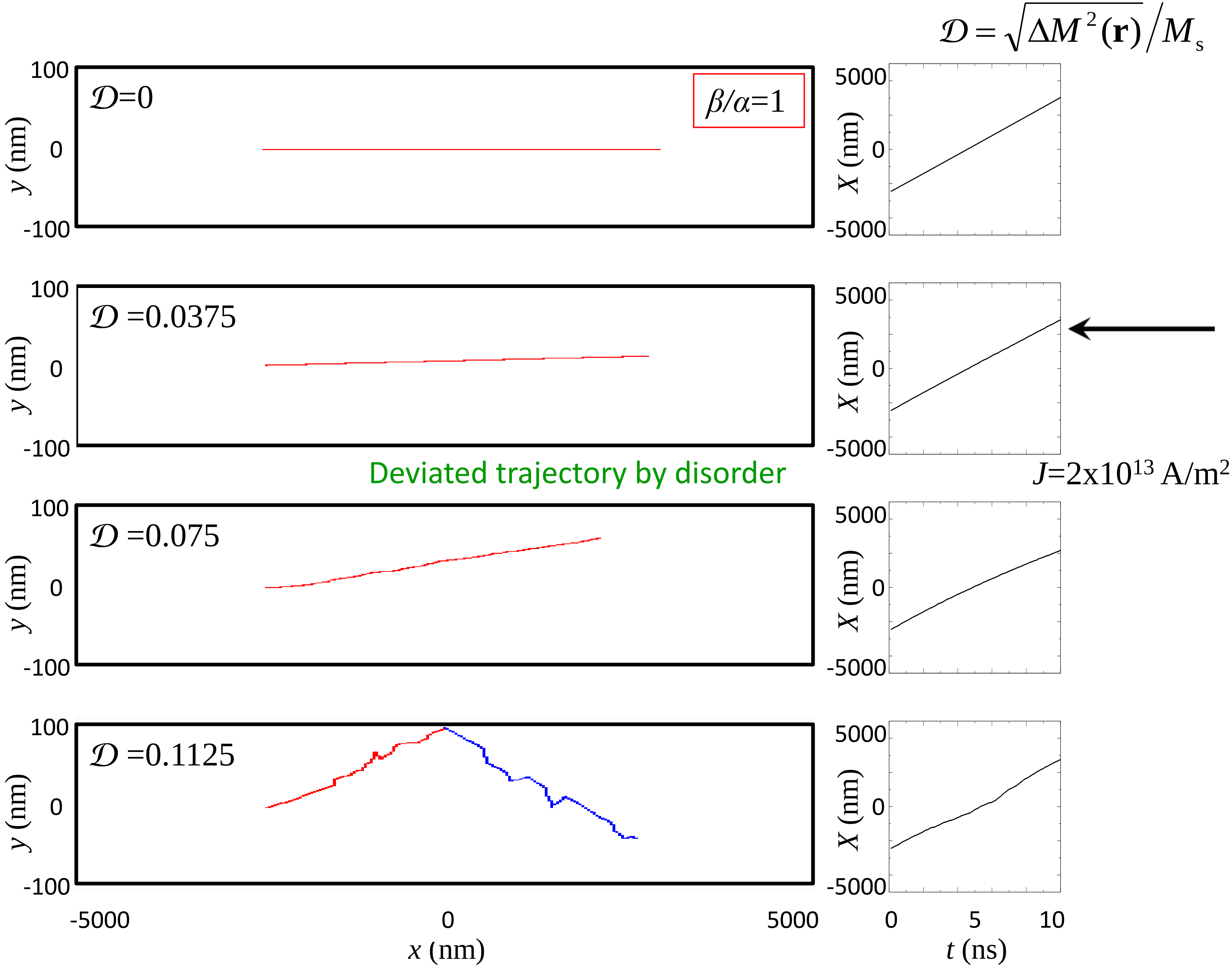
$\mathbf{V}$ = domain wall velocity
$\mathbf{D}$ = viscosity tensor
$\mathbf{F}$ = generalized force
$\mathbf{G}$ = gyroscopic tensor

Ideal model with different β/α

Changing α in high current regime: $v_s=2.5v_c(\beta=0)$

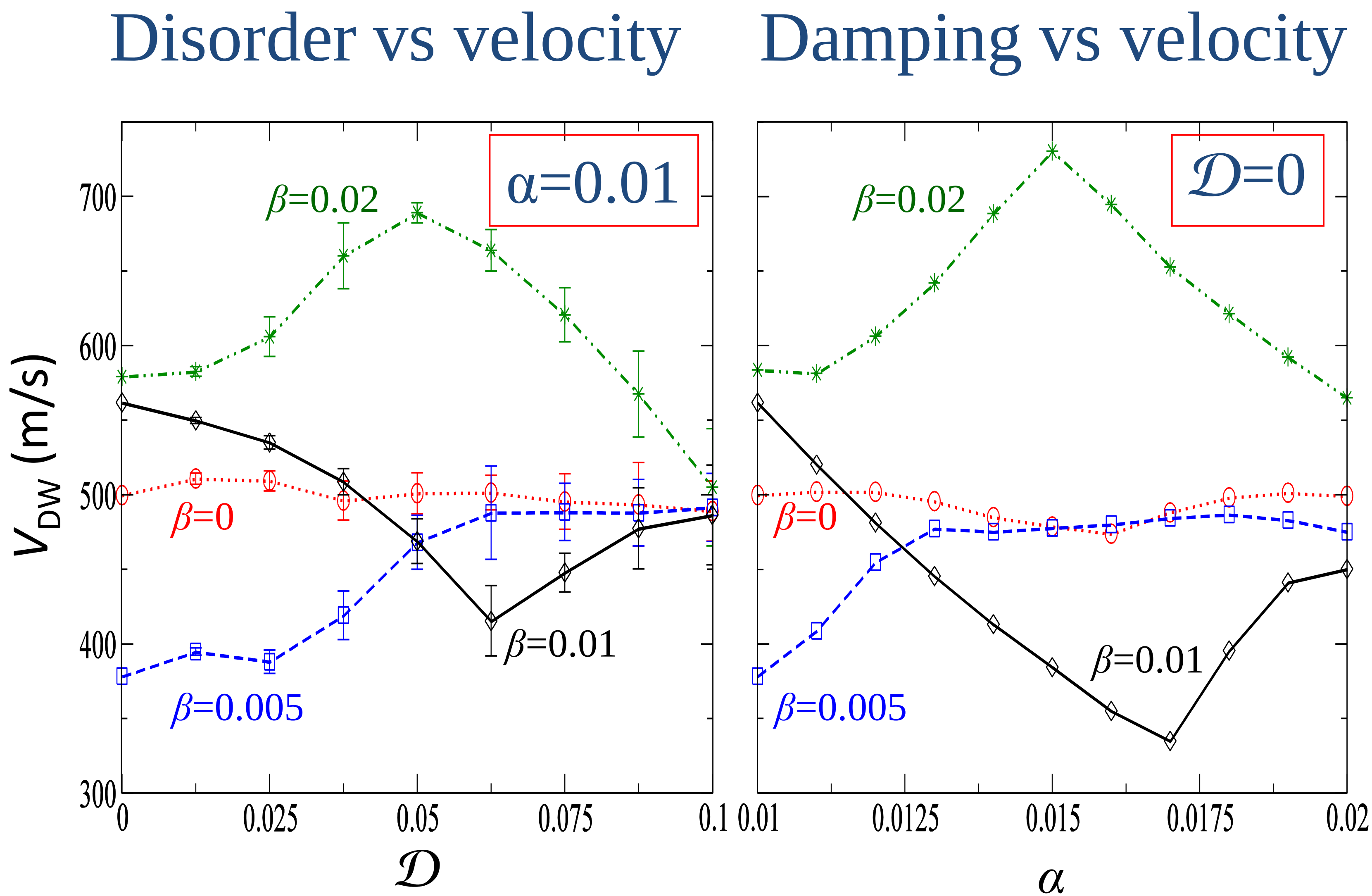


Trajectories depend on β/α



$\mathcal{D}=\sqrt{\Delta M^2(\mathbf{r})}/M_s$
$\mathcal{D}$=0
β/α=1
$\mathcal{D}$ =0.0375
Deviated trajectory by disorder
J=2x10^{13} A/m^2
$\mathcal{D}$ =0.075
$\mathcal{D}$ =0.1125
100
0
-100
y (nm)
5000
0
-5000
X (nm)
-5000
0
5000
x (nm)
0
5
10
t (ns)

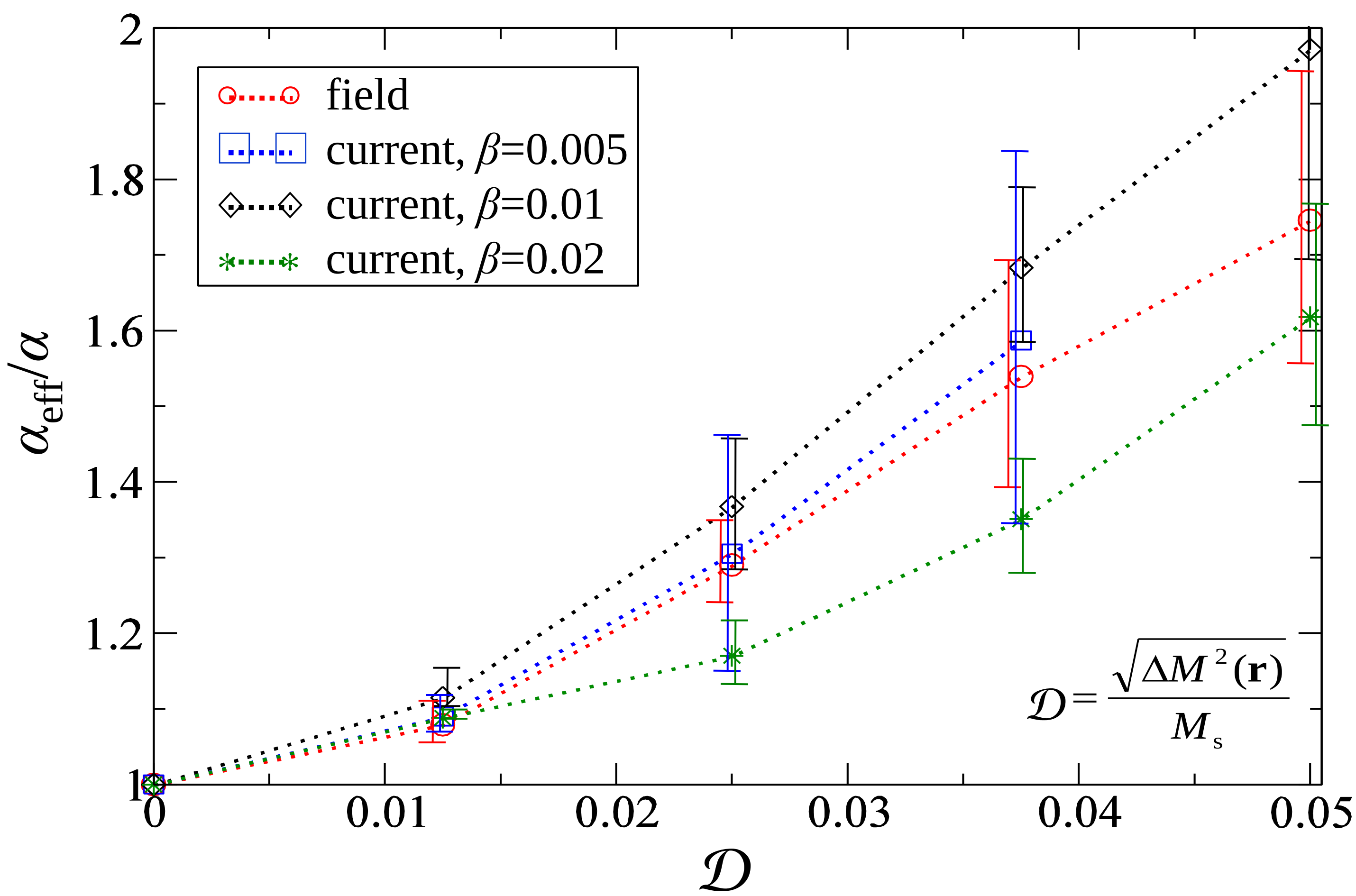
Disorder enhances the effective damping



$J=2\mathrm{x}10^{13}\ \mathrm{A/m}^2 > J_{c,\ \beta=0}$

Disorder enhances the effective damping

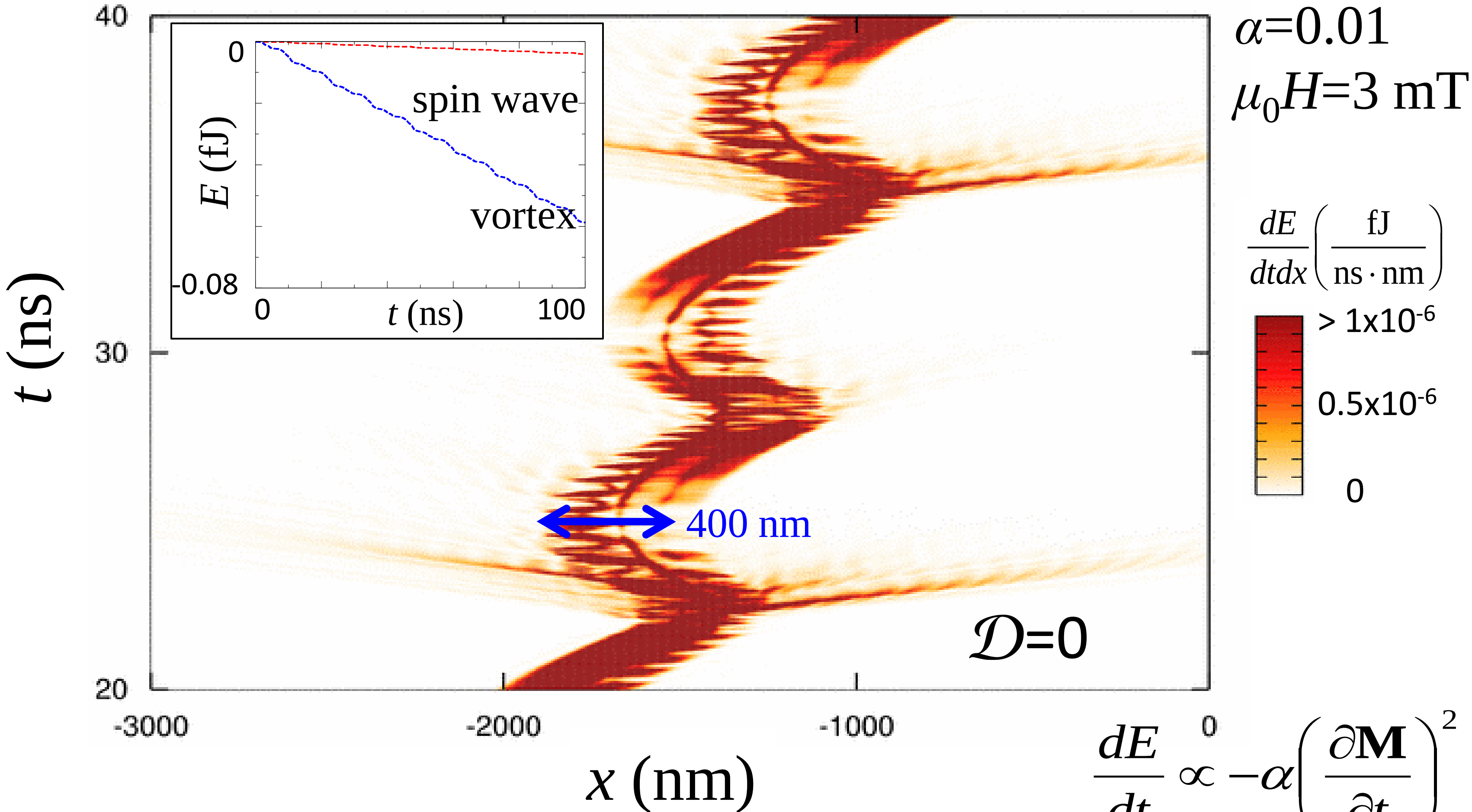
Domain wall velocity as a function of disorder



Extracted effective damping constant could vary sample by sample

Energy dissipation

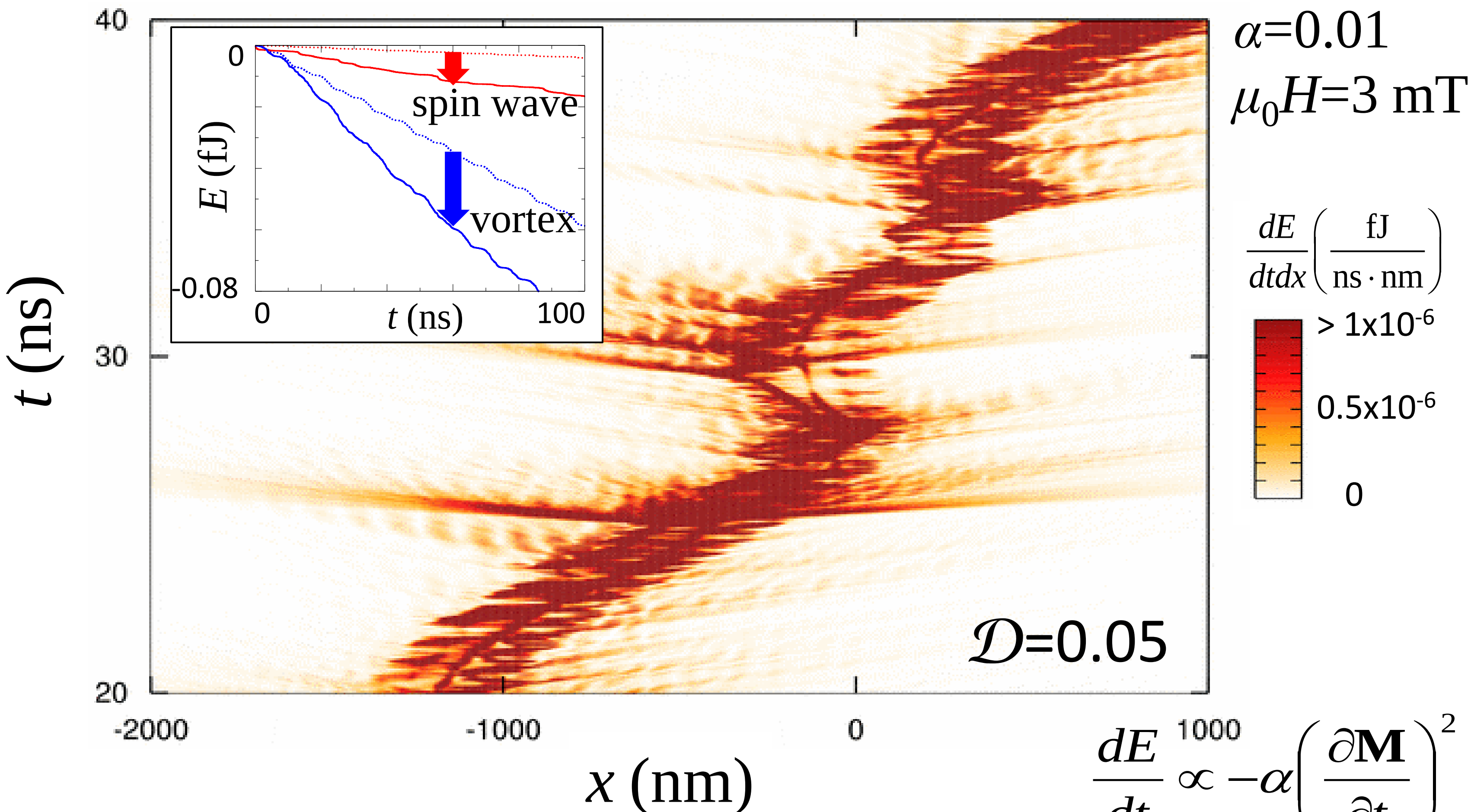
Dissipation through spin wave and vortex core



$$\frac{dE}{dt} \propto -\alpha\left(\frac{\partial \mathbf{M}}{\partial t}\right)^2$$

Energy dissipation

Dissipation through spin wave and vortex core



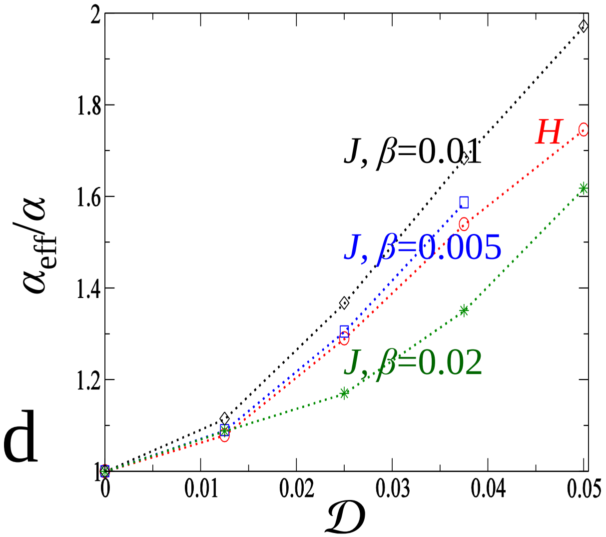
$$\frac{dE}{dt} \propto -\alpha\left(\frac{\partial \mathbf{M}}{\partial t}\right)^2$$

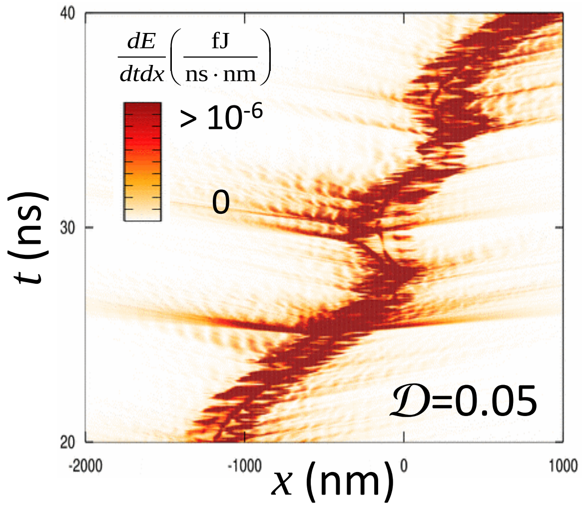
Increased rate of energy dissipation from vortex core motion indicates excitation of the internal degrees of freedom in domain wall structure.

Summary of Part I

Min *et al*, PRL **104**, 217201 (2010)

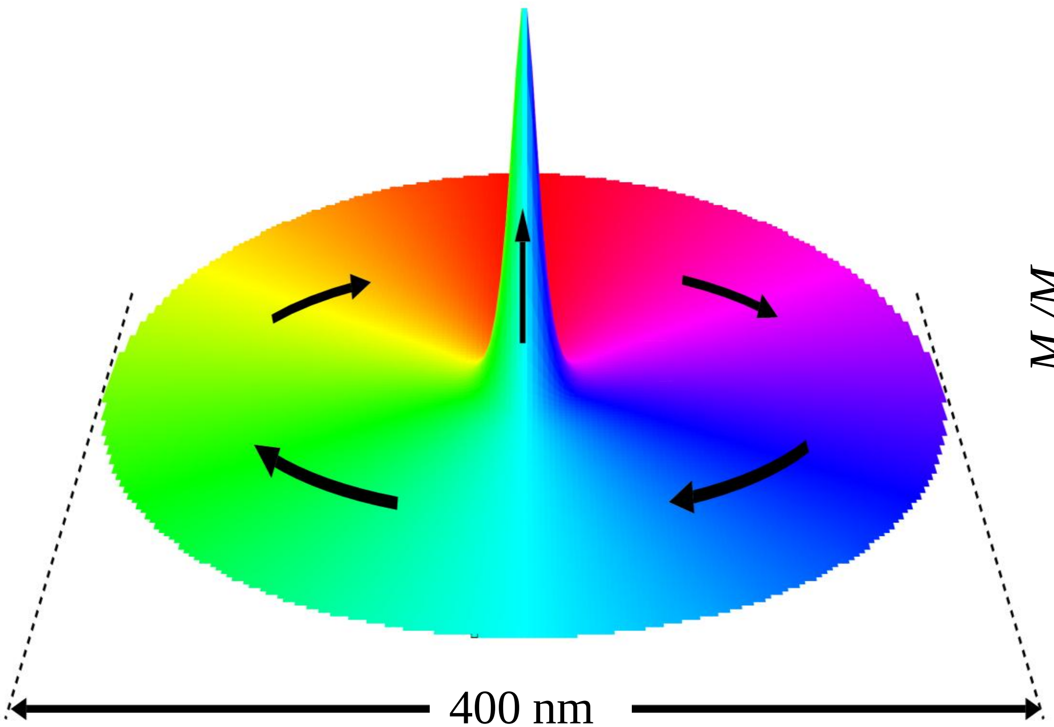
- Disorder can affect domain wall dynamics significantly.
- Excitation of internal degrees of freedom by disorder gives enhanced effective damping.
- Caution is needed when using idealized models to interpret domain wall motion measurements.

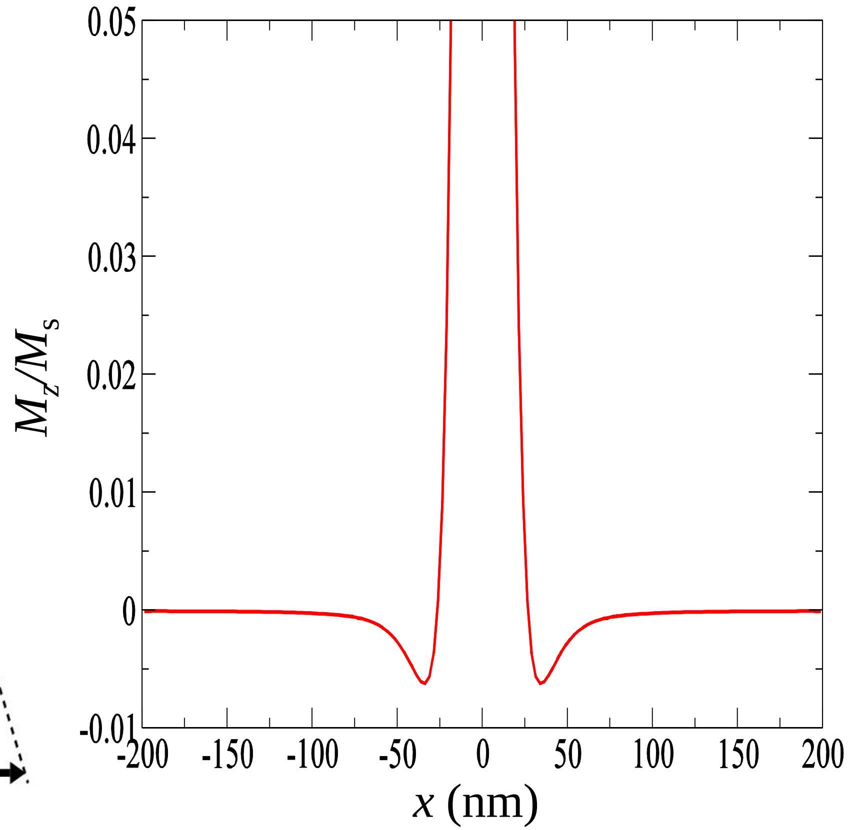




Vortex in a magnetic disk

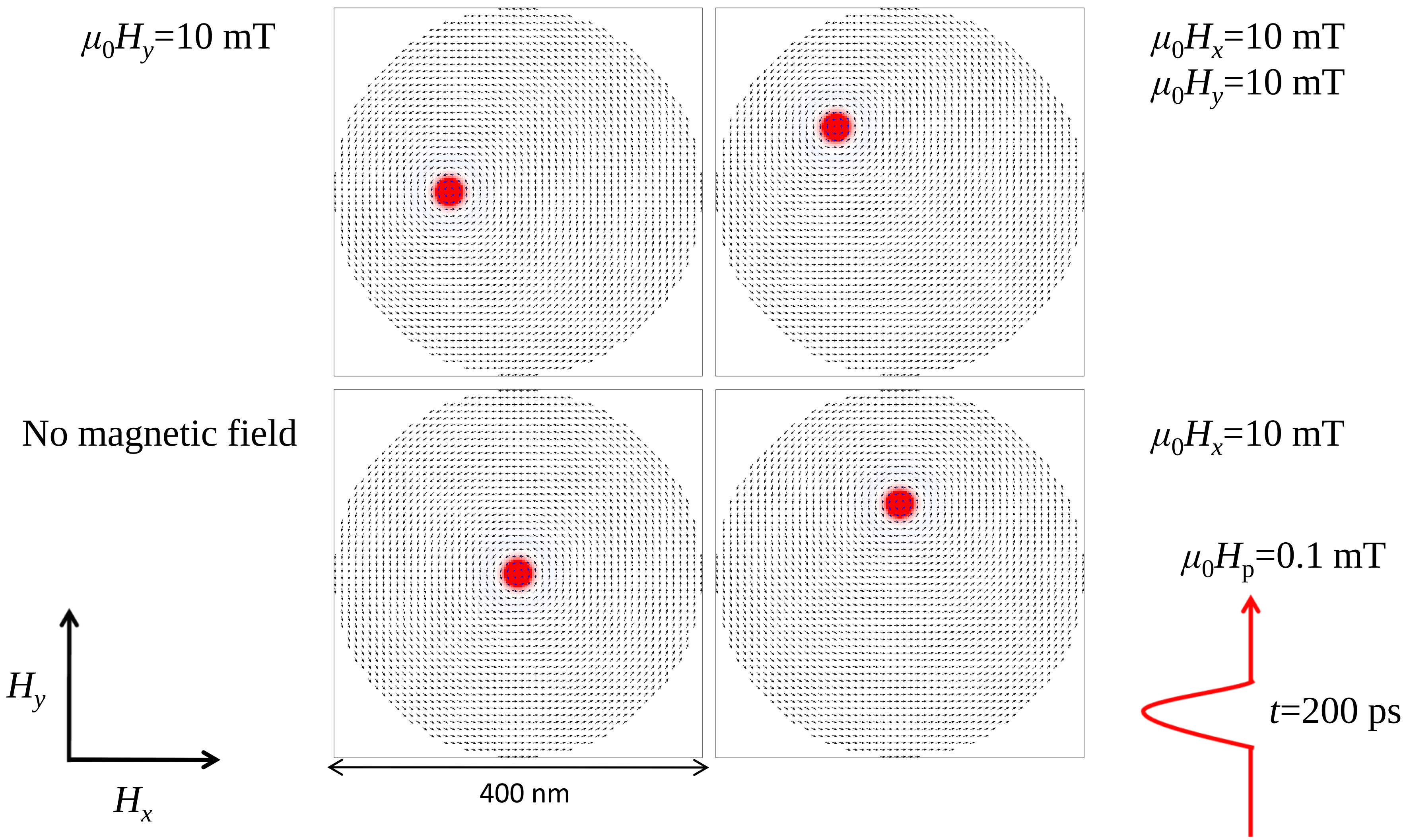
Diameter=400 nm, thickness=10 nm, cell=2.5 nm





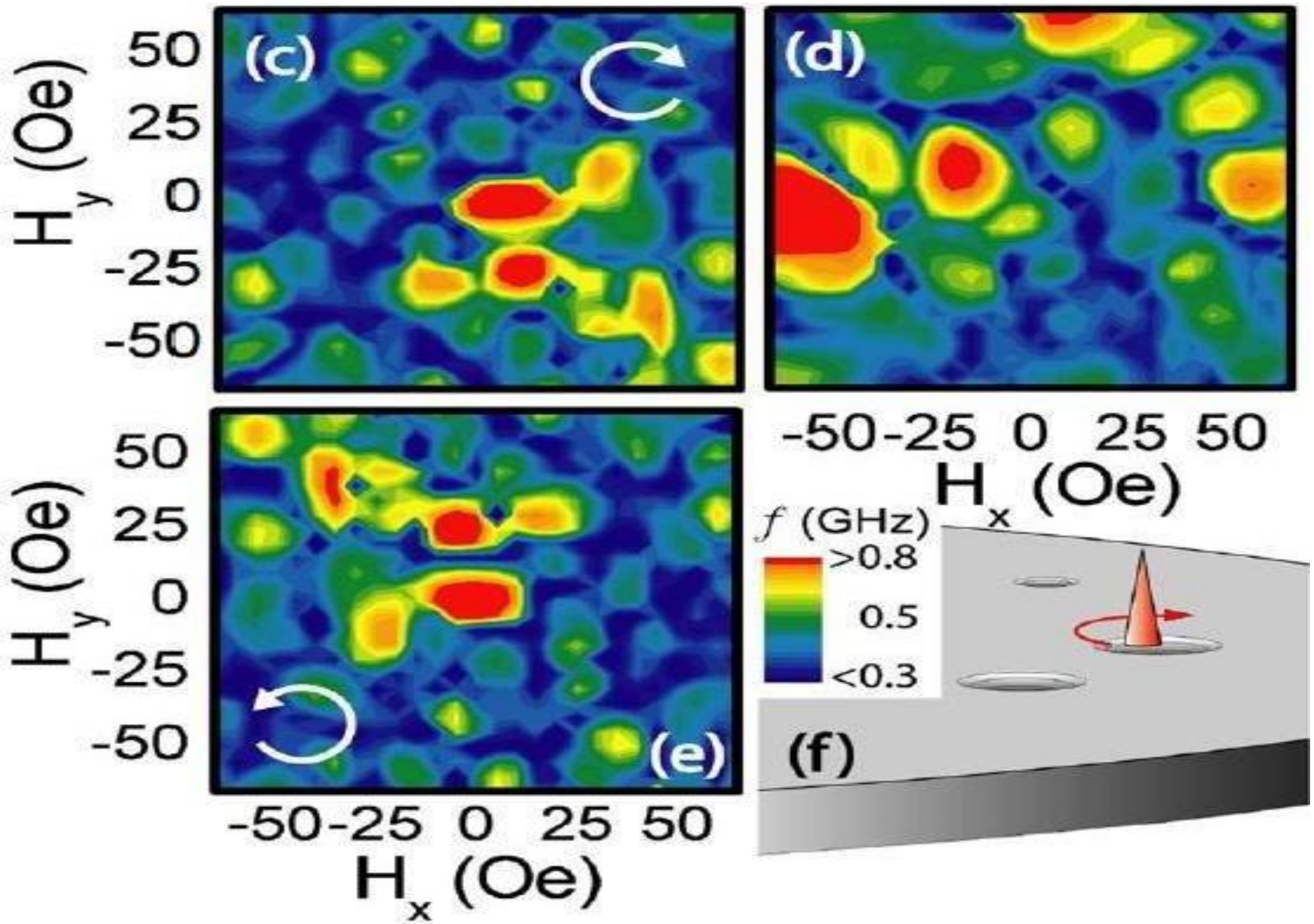
Study the enhanced damping ratio in vortex gyration

Displacement of vortex core by static fields



Gyration frequency map from Kerr microscopy

Compton and Crowell, PRL **97**, 137202 (2007);
Compton, Chen and Crowell, PRB **81**, 144412 (2010)

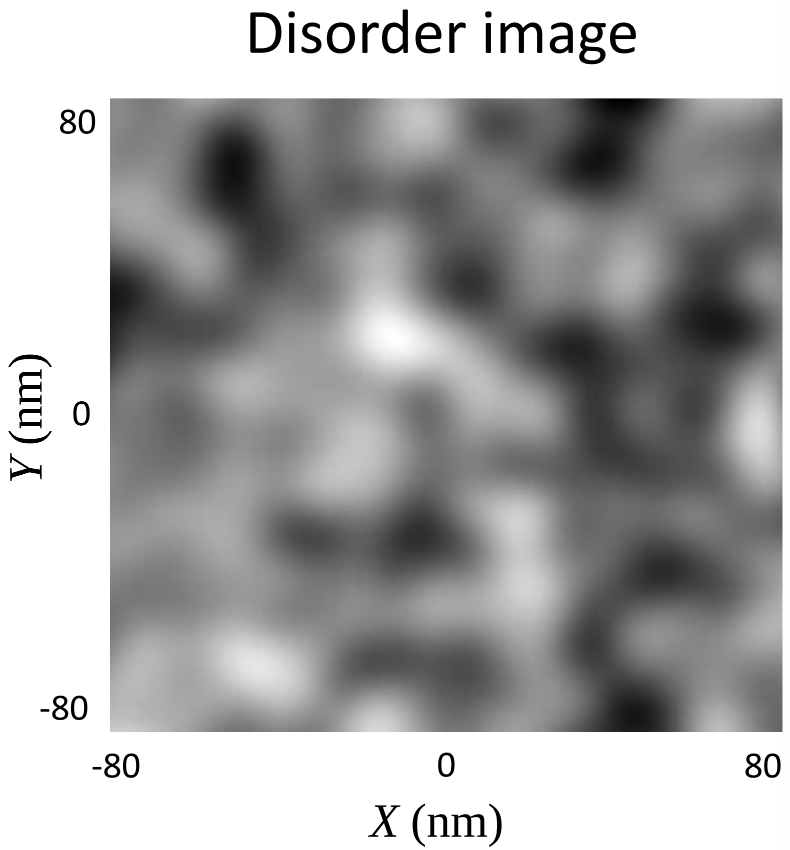


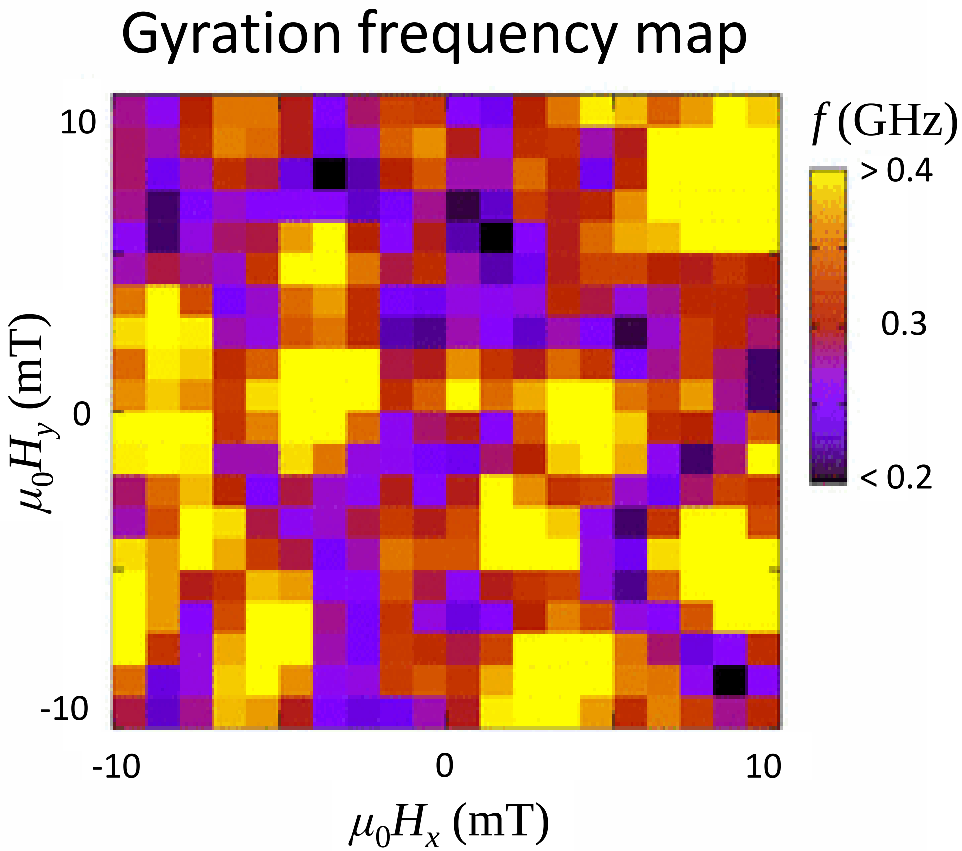
Gyration with a frequency that is a characteristic of a pining site

Gyration frequency map from simulation

$\mathcal{D}$=0.05, $\mu_0 H_p$=0.1 mT, dt_p=0.2 ns

$$\mathcal{D} = \sqrt{\Delta M^2(\mathbf{r})} / M_s$$





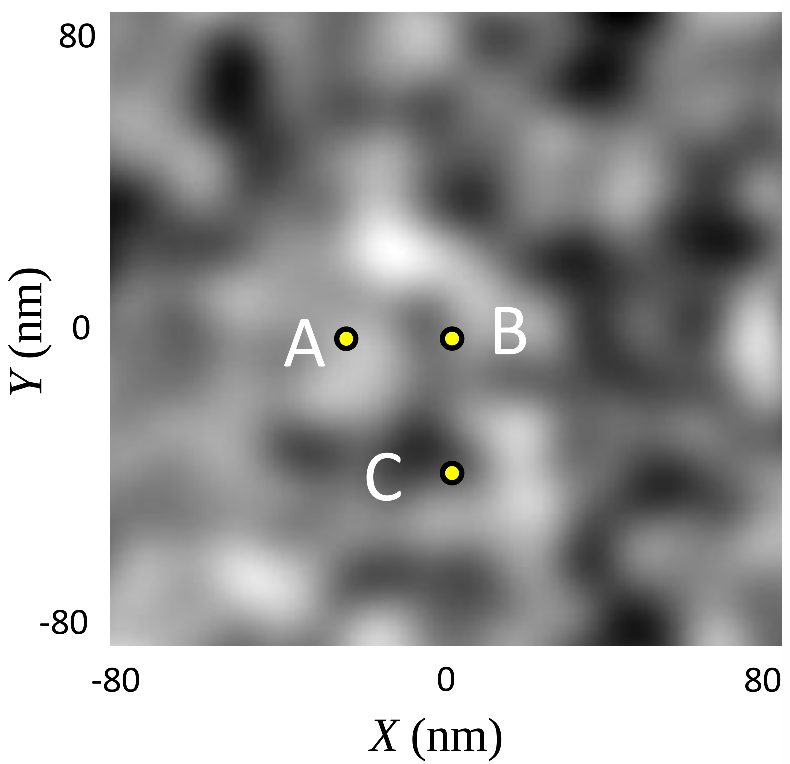
Gyration with a frequency that is a characteristic of a pining site

Gyration frequency map from simulation

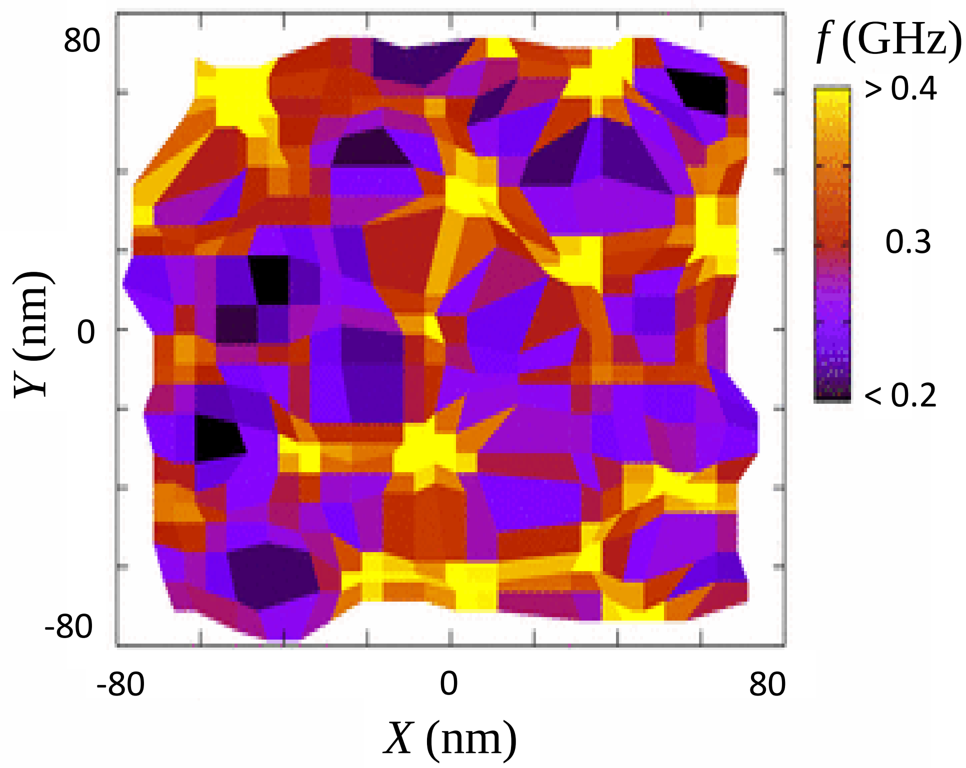
$\mathcal{D}$=0.05, $\mu_0 H_p$=0.1 mT, dt_p=0.2 ns

$$\mathcal{D} = \sqrt{\Delta M^2(\mathbf{r})} / M_s$$

Disorder image



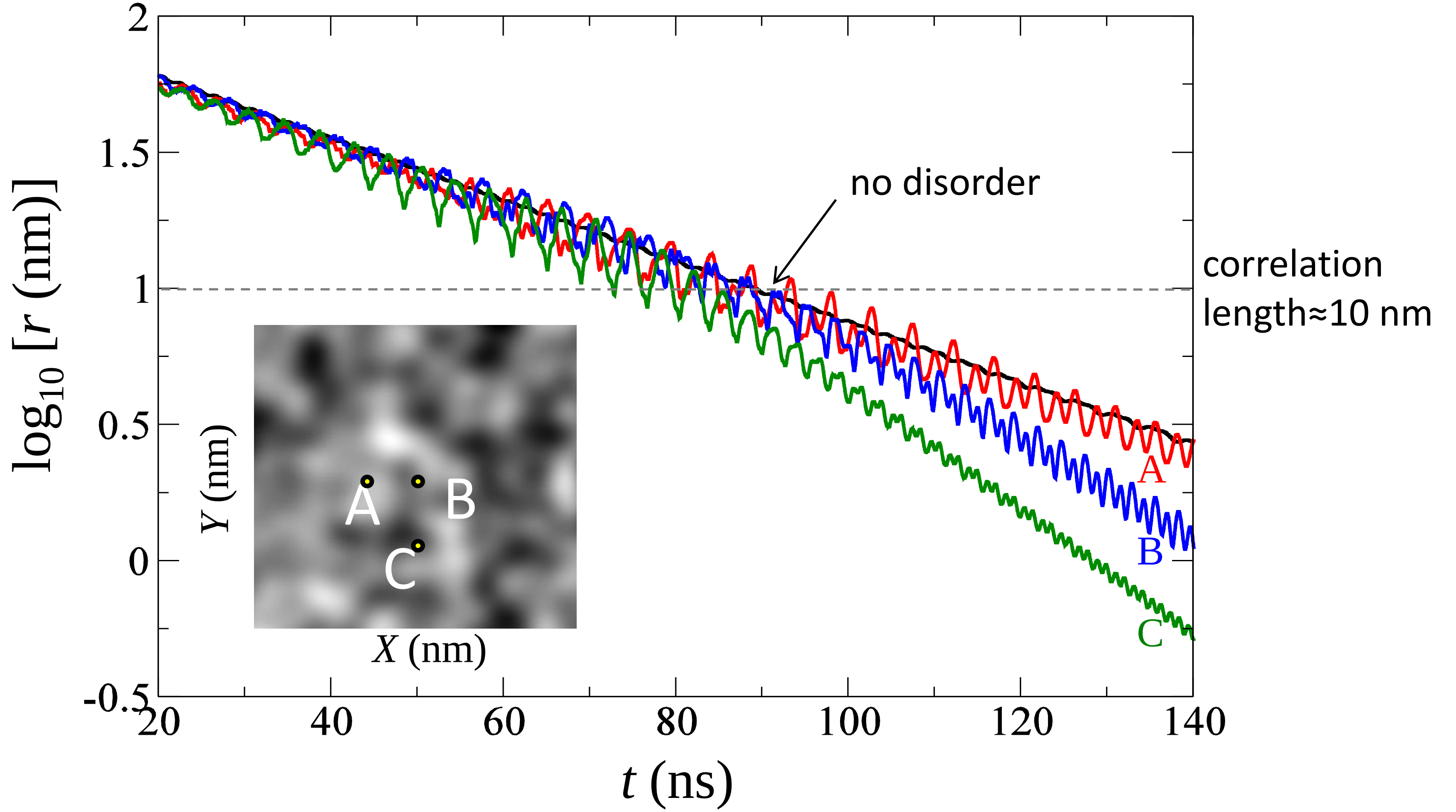
Gyration frequency map



Gyration with a frequency that is a characteristic of a pining site

Time evolution of gyration radius

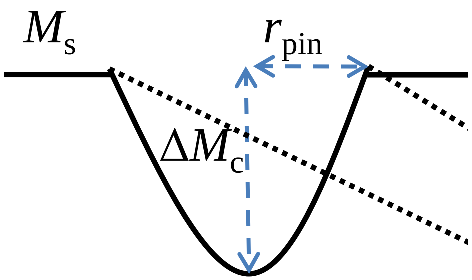
$\mathcal{D}=0.05$, $\mu_0 H_p=20$ mT, $dt_p=1$ ns



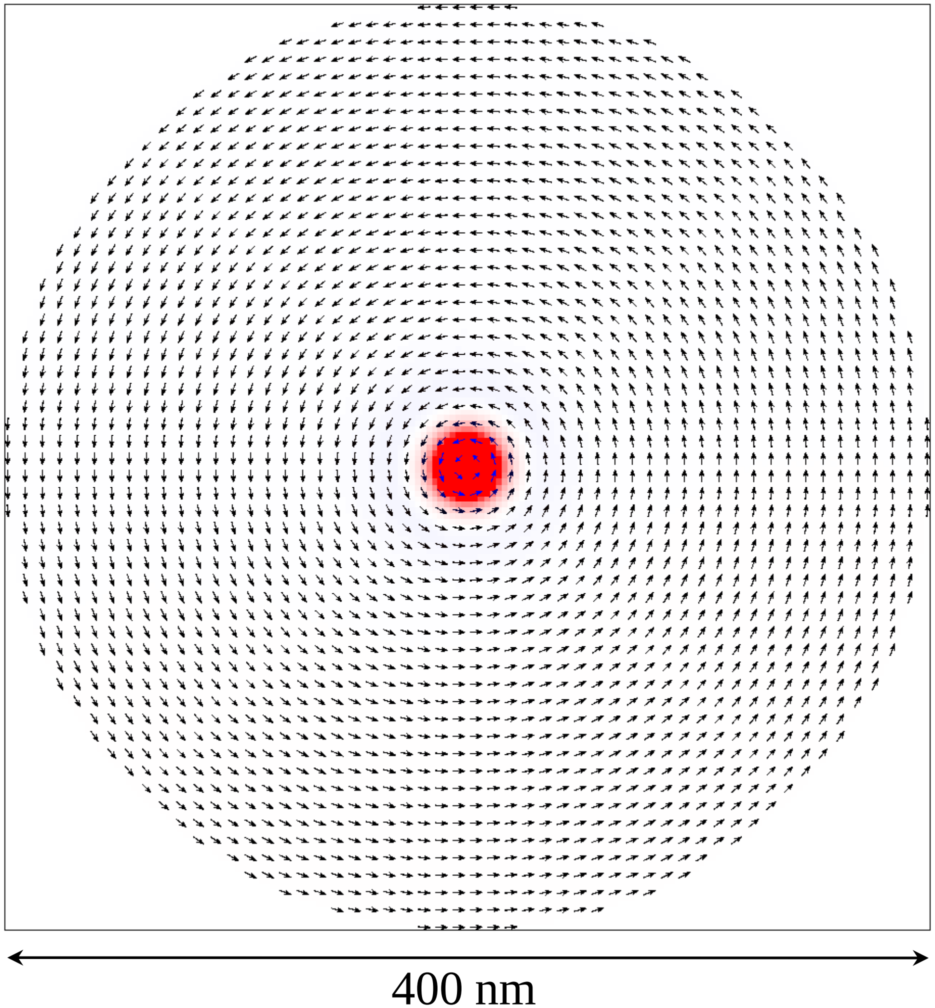
Transition from free to trapped regimes

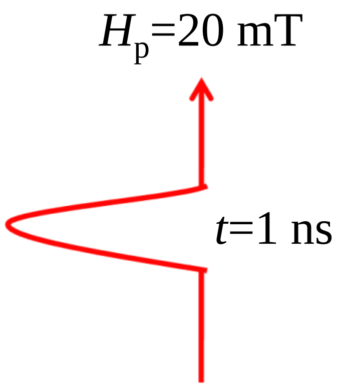
Vortex gyration in a single pinning potential

Single pinning potential with a radius of 10 nm



$$\delta = \frac{\Delta M_c}{M_s}$$





Collective coordinate approach

Two-coordinate model for vortex core position

- Equations of motion $\boxed{(X, Y)}$

$$\boxed{\alpha \mathbf{D}\mathbf{V} = \mathbf{F} + \mathbf{V} \times \mathbf{G}}$$

$\mathbf{V} =$ time derivative of (X,Y)
$\mathbf{D} =$ viscosity tensor
$\mathbf{F} =$ generalized force
$\mathbf{G} =$ gyroscopic tensor
$\alpha =$ Gilbert damping

$$R = R_0 \exp\left(-\frac{t}{\tau}\right), \quad \phi = 2\pi f t$$

$$\Rightarrow \boxed{2\pi f \tau C \alpha = 1} \qquad C = \frac{D_{\phi\phi}}{G + \alpha D_{R\phi}}$$

Geometrical factor

$$\Rightarrow \boxed{\frac{f_0 \tau_0}{f \tau} = \frac{\alpha_{\text{eff}} C}{\alpha_0 C_0}}$$

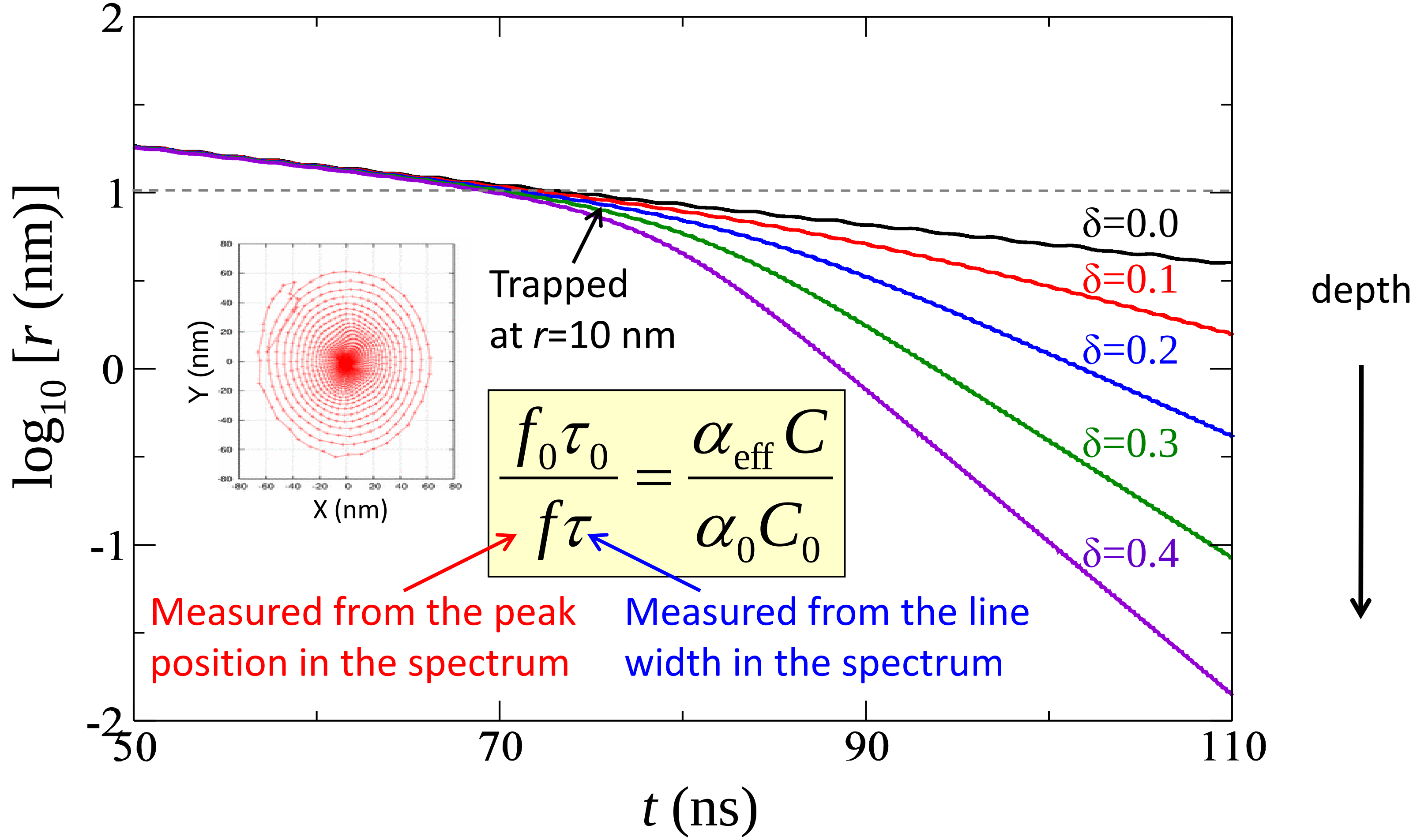
Guslienko *et al*, JAP **91**, 8037 (2002);
Guslienko *et al*, PRB **71**, 144407 (2005);
Guslienko, APL **89**, 022510 (2006);
Guslienko *et al*, PRL **100**, 027203 (2008);
Vansteenkiste *et al*, NJP **11**, 063006 (2009);
Apolonio *et al*, JAP **106**, 084329 (2009);
…..

By comparing free and trapped regimes, the effective damping can be determined.

Enhanced decay rate by a pinning potential

Evolution of gyration radius

$$\delta = \Delta M_c / M_s$$



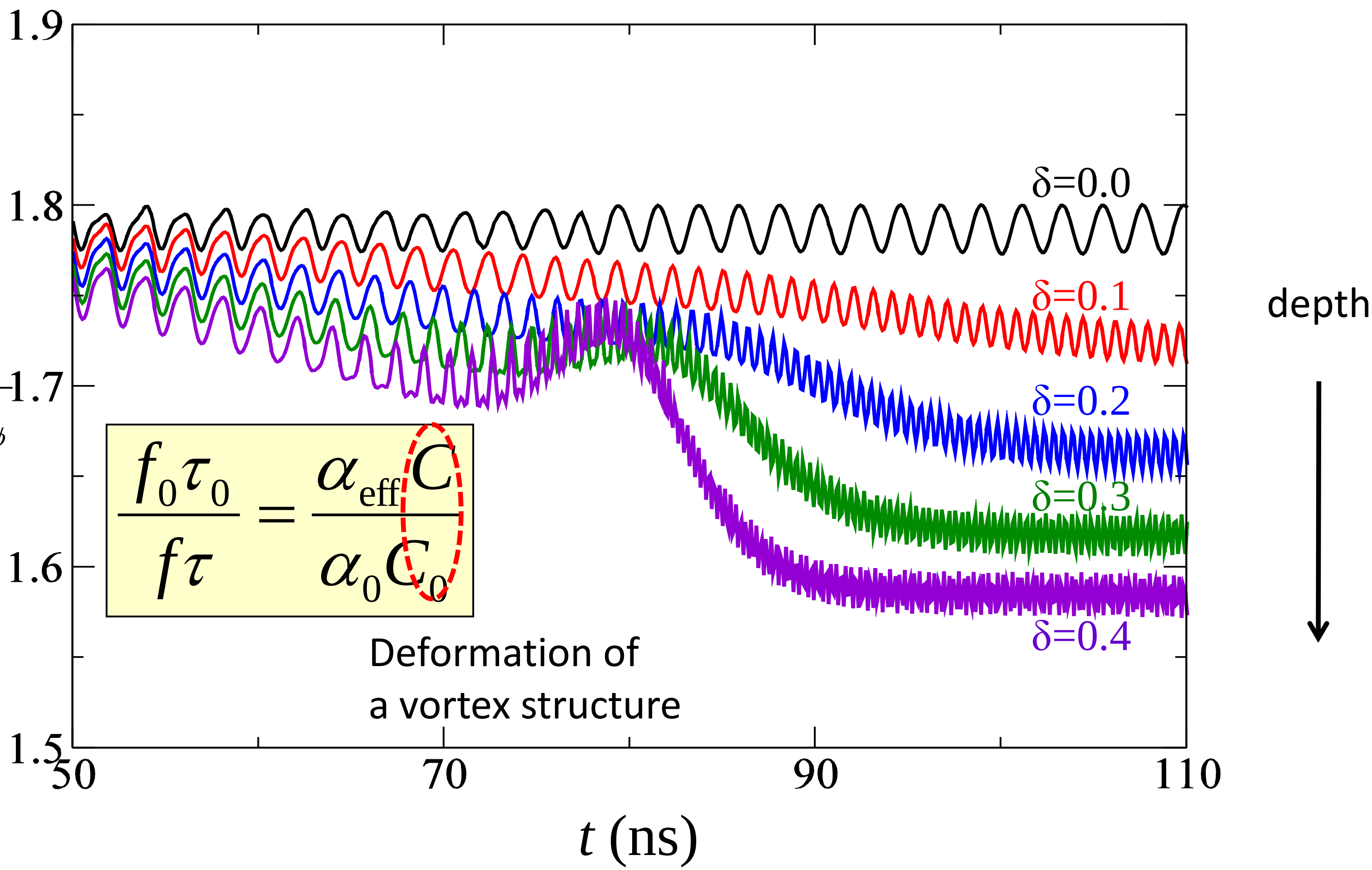
Transition from free to trapped regimes

Deformation by a pinning potential

Evolution of deformation factor

$$\delta = \Delta M_c / M_s$$

$$C = \frac{D_{\phi\phi}}{G + \alpha D_{R\phi}}$$

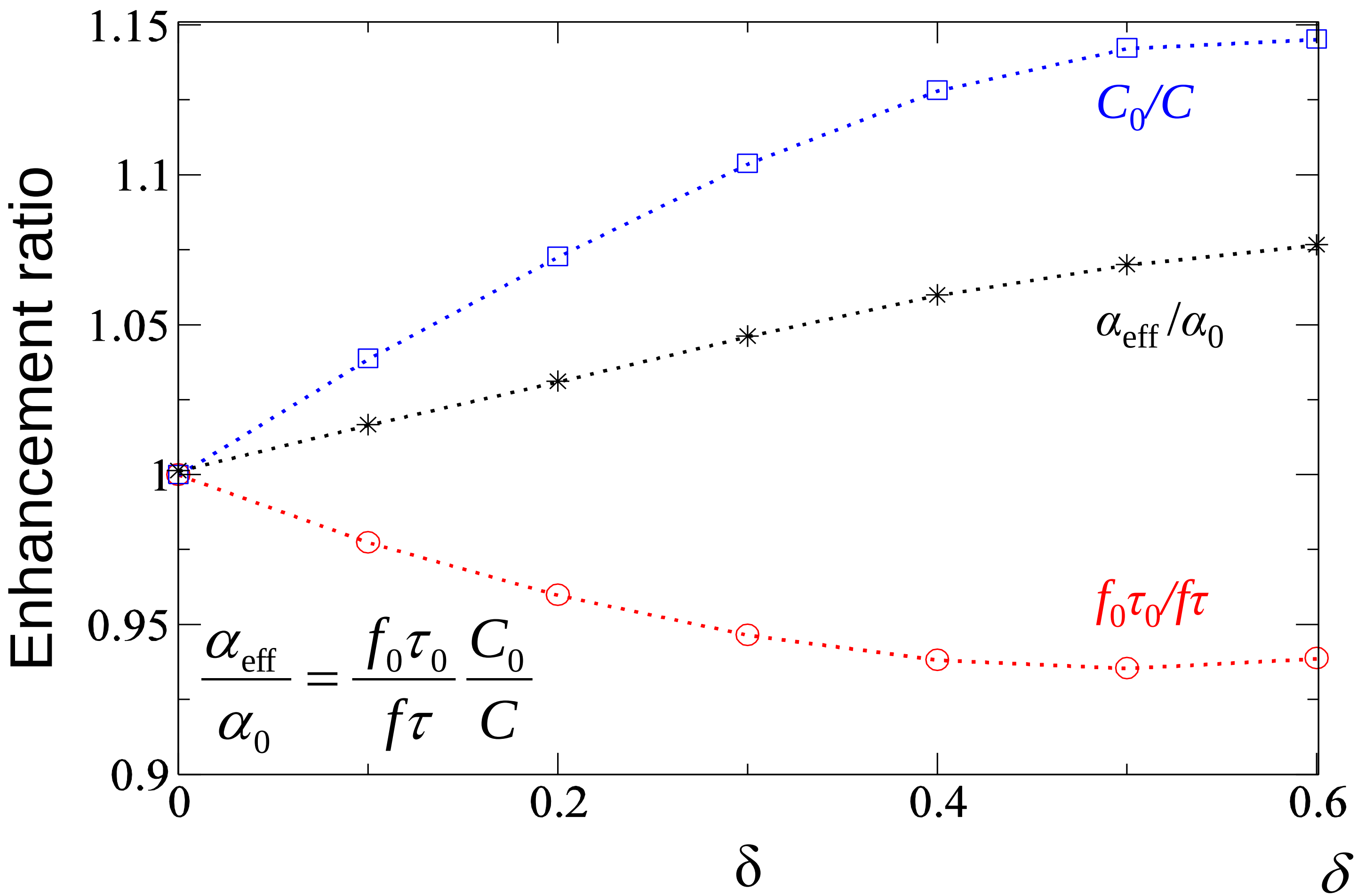


$$\frac{f_0 \tau_0}{f \tau} = \frac{\alpha_{\mathrm{eff}} C}{\alpha_0 C_0}$$

Deformation of vortex should be taken into account

Enhanced effective damping

Enhancement ratio as a function of depth

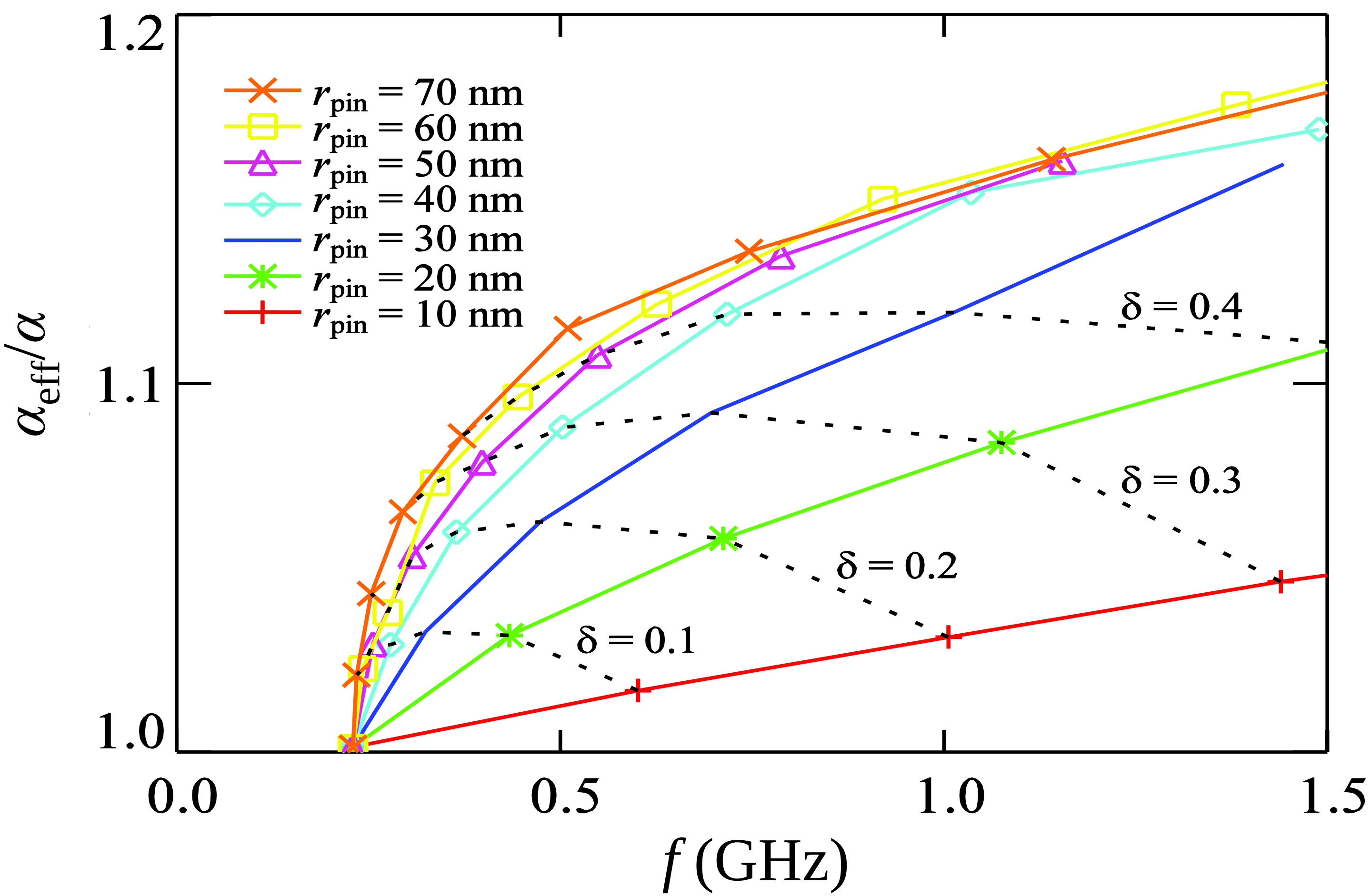


$$\delta = \frac{\Delta M_c}{M_s}$$

Enhanced damping mostly comes from the change in geometry of the vortex.

Enhanced effective damping

Effective damping as a function of frequency



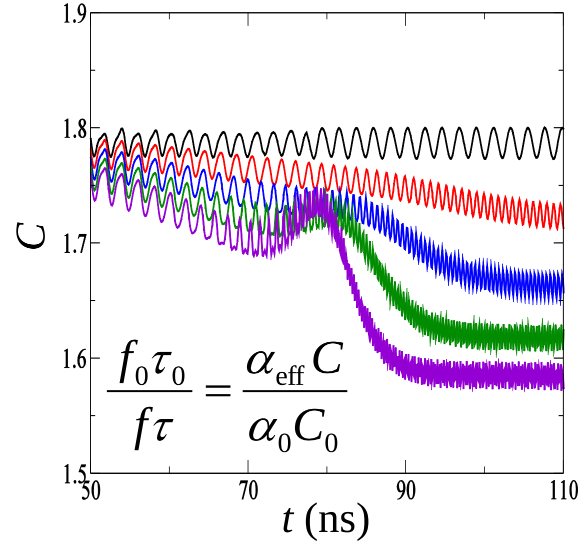
As the frequency increases, the vortex gets more excited increasing the effective damping.

Summary of Part II

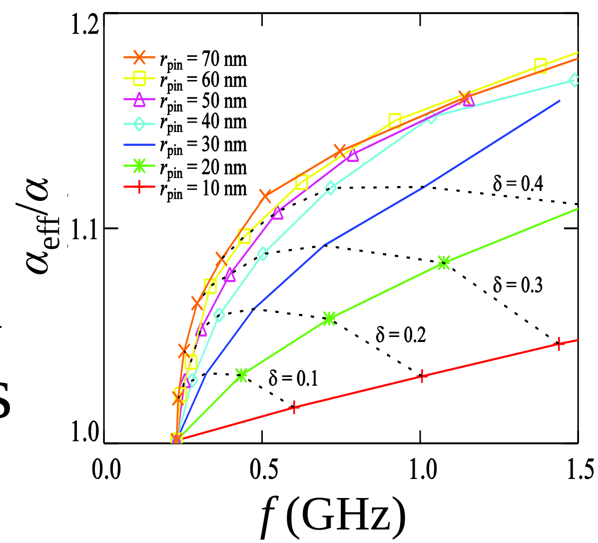
Min *et al*, PRL **104**, 217201 (2010)

Min *et al*, PRB **83**, 064411 (2011)

- The enhanced damping rate could be measured by the gyration experiments up to the deformation factor.



- The larger the gyration frequency, the bigger the effective damping.



- The effective damping is enhanced by disorder and internal excitations of domain wall structure.

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