Center for Computational Sciences and Simulation

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# Magnetic Friction of Vortices

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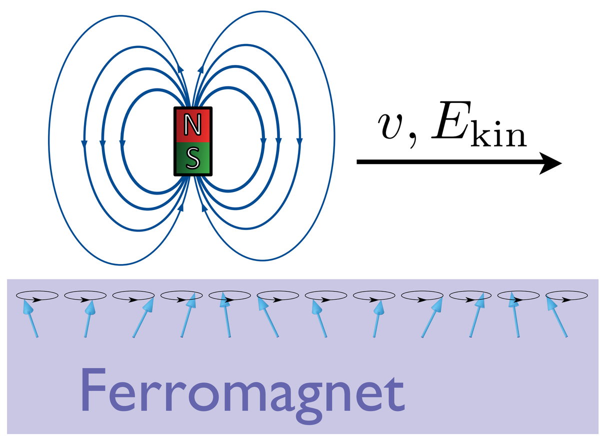
## Motivation

- Development of a model for energy dissipation in a purely magnetically interacting system
- A magnetic dipole is moved parallel to a magnetic material, analogous to the scanning tip of a magnetic force microscope or the reading head of a hard disk
- Tip induces magnons in the substrate [1,2]
- Vortex structures feel a strong friction force




## Atomistic model

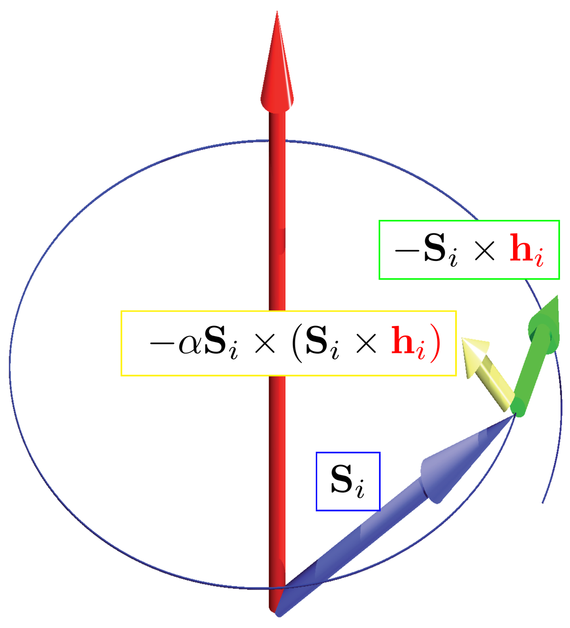
- Single atoms are modeled by normalized magnetic moments ("spins" $\mathbf{S}_i = \boldsymbol{\mu}_i/\mu_s$) on a grid $L_x \times L_y$ with lattice constant $a$
- Substrate spins undergo ferromagnetic exchange interaction $J > 0$ and anisotropy with constant $d_z < 0$ (easy plane)

$$\mathcal{H}_{\mathrm{sub}} = -J \sum_{\langle i,j \rangle} \mathbf{S}_i \cdot \mathbf{S}_j - d_z \sum_i S_{i,z}^2$$

- Substrate spins interact with tip by dipole-dipole interaction

$$\mathcal{H}_{\mathrm{tip}} = -w \sum_i \frac{3(\mathbf{S}_i \cdot \mathbf{e}_{i,\mathrm{tip}})(\mathbf{S}_{\mathrm{tip}} \cdot \mathbf{e}_{i,\mathrm{tip}}) - \mathbf{S}_i \cdot \mathbf{S}_{\mathrm{tip}}}{r_{i,\mathrm{tip}}^3}$$

- Tip magnetization is fixed in $z$-direction, and moved with velocity




- Substrate spins are evolved in time by integration of the Landau-Lifshitz-Gilbert equation of motion [3,4]

$$\frac{(1+\alpha^2)\mu_s}{\gamma} \frac{\partial}{\partial t} \mathbf{S}_i = -\mathbf{S}_i \times \mathbf{h}_i - \alpha \mathbf{S}_i \times (\mathbf{S}_i \times \mathbf{h}_i)$$

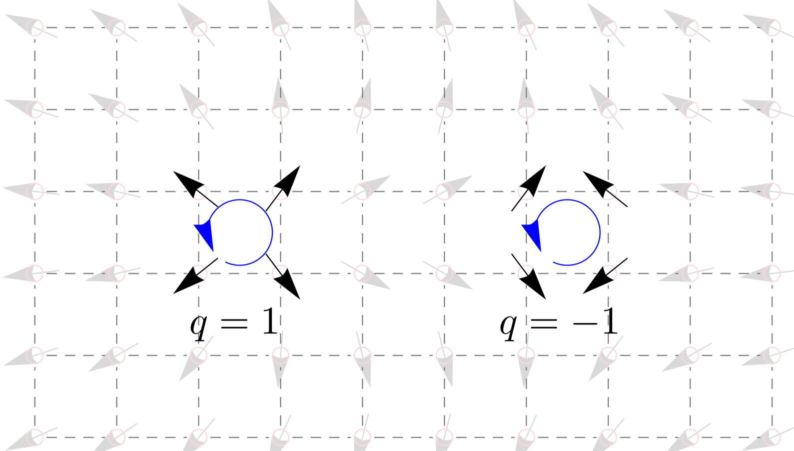
with saturation magnetization $\mu_s$, the phenomenological damping constant $\alpha$, the gyromagnetic ratio $\gamma$

- Local field is coupled to a heat bath:

$\mathbf{h}_i = -\frac{\partial \mathcal{H}}{\partial \mathbf{S}_i} + \boldsymbol{\zeta}_i(t)$ with mean $\langle \boldsymbol{\zeta}_i(t) \rangle = 0$ and correlator $\langle \zeta_i^\kappa(t) \zeta_j^\lambda(t') \rangle = 2 \frac{\alpha \mu_s k_B T}{\gamma} \delta_{i,j} \delta_{\kappa,\lambda} (t - t')$

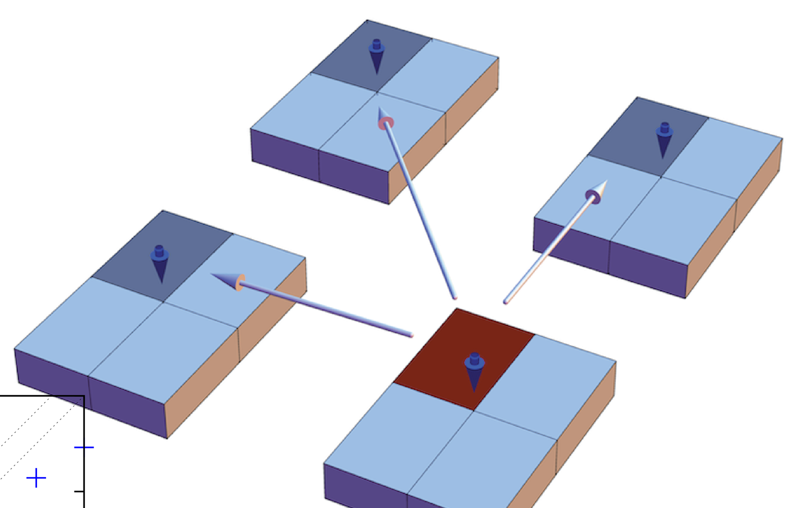
- Total magnetization $m = \frac{1}{L_x L_y} \left| \sum_{i=1}^{L_x L_y} \mathbf{S}_i \right|$
- Lattice vorticity $q_i = \frac{1}{2\pi} \sum_{\circlearrowleft_i} \Delta\phi$

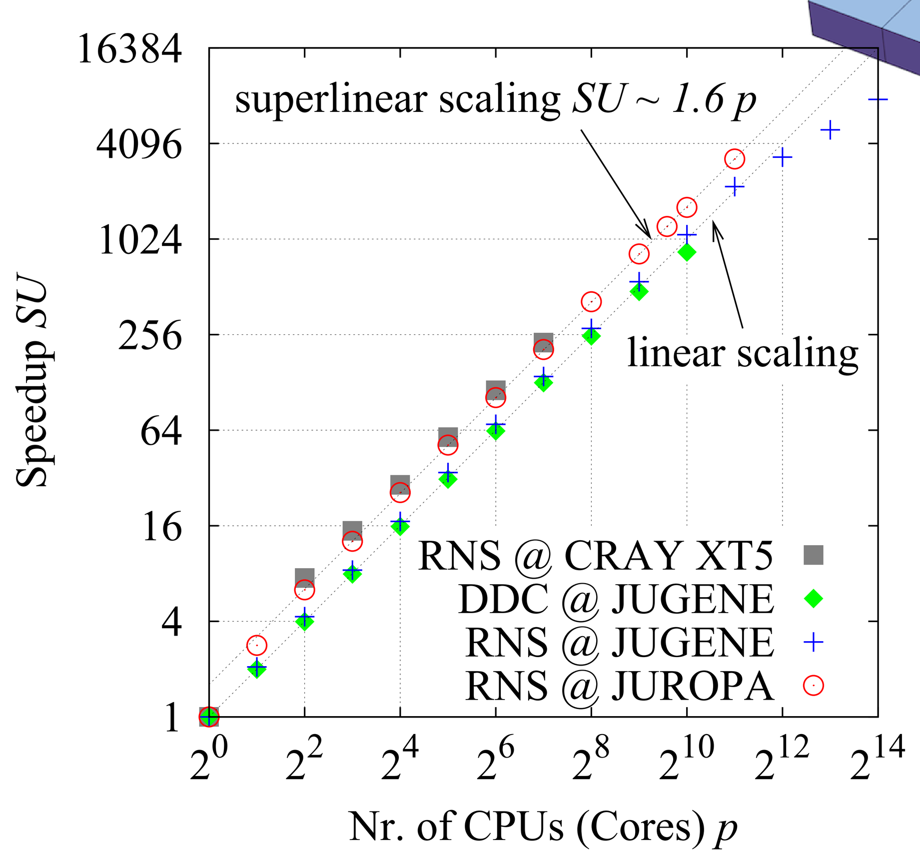
with $q_i \in \mathbb{Z}$, $Q = \sum |q_i|$




## Parallelization

- Absence of long-range interactions yields efficient domain decomposition (DDC)
- The parallel use of random numbers (RNS) leads to a superlinear scaling






## References

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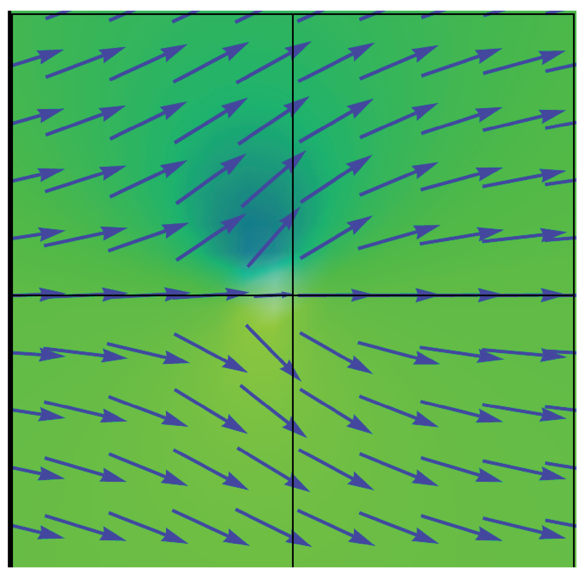
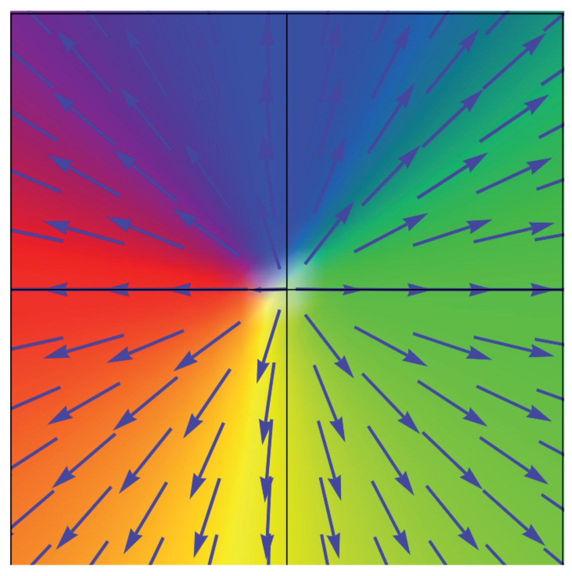
[2] M.P. Magiera, L. Brendel, D.E. Wolf and U. Nowak, *Europhys. Lett.* **95**, 17010 (2011)
[3] L.D. Landau and E.M. Lifshitz, *Phys. Z. Sowjetunion* **8**, 153 (1935)
[4] T.L . Gilbert, *IEEE Trans. Magn.* **40**, 3443 (2004)
[5] D. L. Huber, *Phys. Rev. B* **26**, 3758 (1982)
[6] M.P. Magiera, S. Angst, A. Hucht and D.E. Wolf, *Phys. Rev. B* **84**, 212301 (2011)
[7] M.P. Magiera, A. Hucht, H. Hinrichsen, S.R. Dahmen and D.E. Wolf, *Europhys. Lett.* **100**, 27004 (2012)
[8] M.P. Magiera, *submitted*

## Ground states at $v = 0$

**C**ollinear **S**tate



**V**ortex **S**tate



- Energy of the ground states can be calculated on a lattice for the FM or in a continuum model for the vortex state:

$$E_{\mathrm{CS}}^{\mathrm{sub}} = 0.2w^2 \qquad E_{\mathrm{VS}}^{\mathrm{sub}} = \pi \log R/a + 1.88$$
$$E_{\mathrm{CS}}^{\mathrm{tip}} = -0.39w^2 \qquad E_{\mathrm{VS}}^{\mathrm{tip}} = -3.5w$$

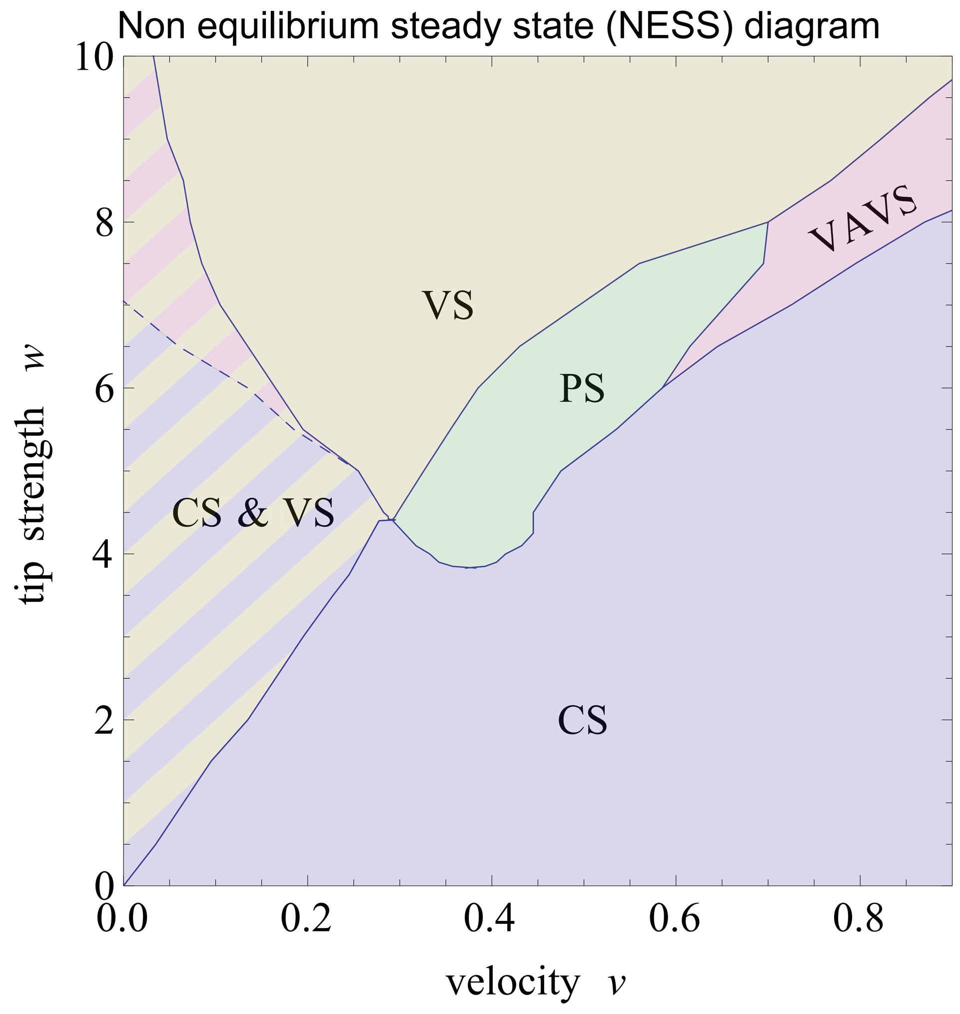
- In the static limit, magnetization and vorticity are

$$m_{\mathrm{CS}} \approx 1 \qquad Q_{\mathrm{CS}} = 0 \qquad m_{\mathrm{VS}} \approx 0 \qquad Q_{\mathrm{VS}} = 1$$

## States observed for $v > 0$ and $T = 0$

- Pure **VS** or **CS** (system always adopts one of them)
- Both, **VS & CS**, are stable
- None of them is stable, we get a periodical switching (**PS**) with time dependent Q=Q(t)
- State with a vortex and an antivortex (**VAVS**), which is bound by the vortex, and which corresponds to Q=2
- Moving the tip may generate or annihilate vortices
- NESSs stable against strong disturbance, e.g. provided by domain walls [7]

Non equilibrium steady state (NESS) diagram




## Periodic state

(a) VS is present, Q=1

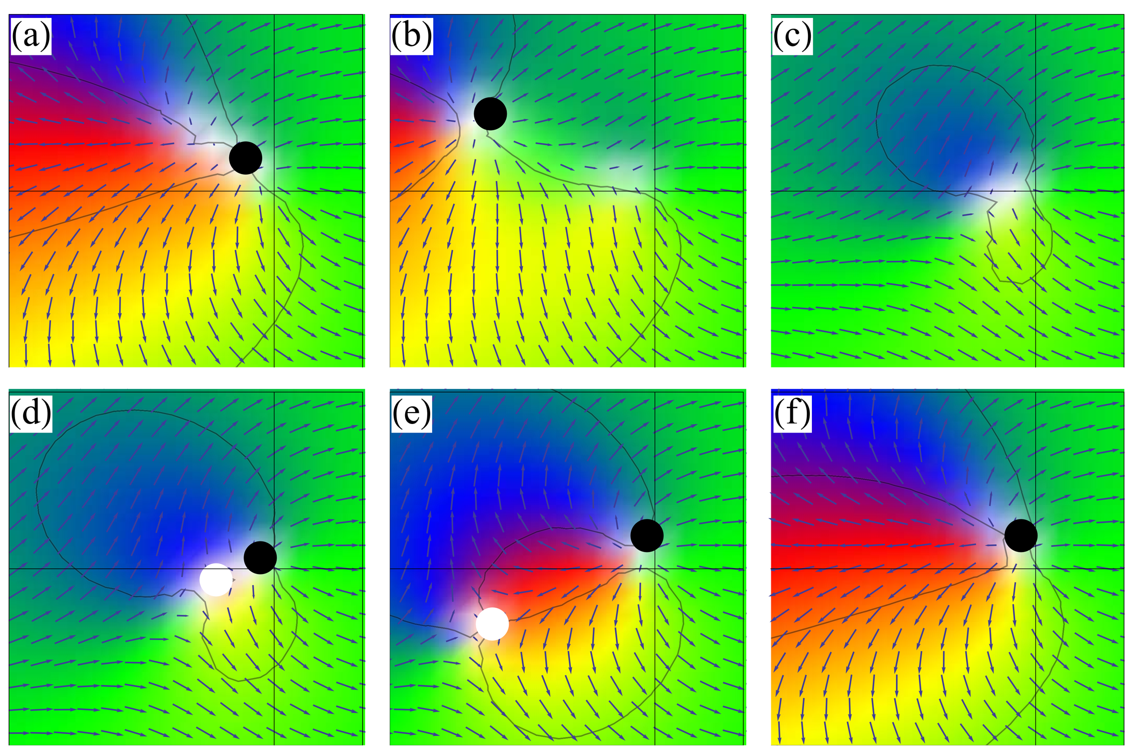
(b) Vortex released from tip

(c) CS is present, Q=0

(d) Vortex-Antivortex pair nucleated, Q=2

(e) Antivortex released from vortex

(f) Vortex is present -> (a)




## Friction force

- The NESS has a large impact on the friction force the tip "feels"
- Friction of the **VS** [5,8]:

$$F = \alpha v \pi \log L/L_0$$

- Friction of the **FM** much weaker, because this structure is not interacting attractively with the tip
- The **PS** shows a friction force between the FM and the **VS**, although here more vortices may be present: but a vortex at rest, detached from the tip, does not dissipate energy

Friction for $\alpha = 0.5$ and $w = 5$