Spin wave propagation and channelling in spin textures driven by the Dzyaloshinskii-Moriya interaction

Joo-Von Kim

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Spin wave propagation and channeling in spin textures driven by the Dzyaloshinskii-Moriya interaction

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Jaivardhan Sinha
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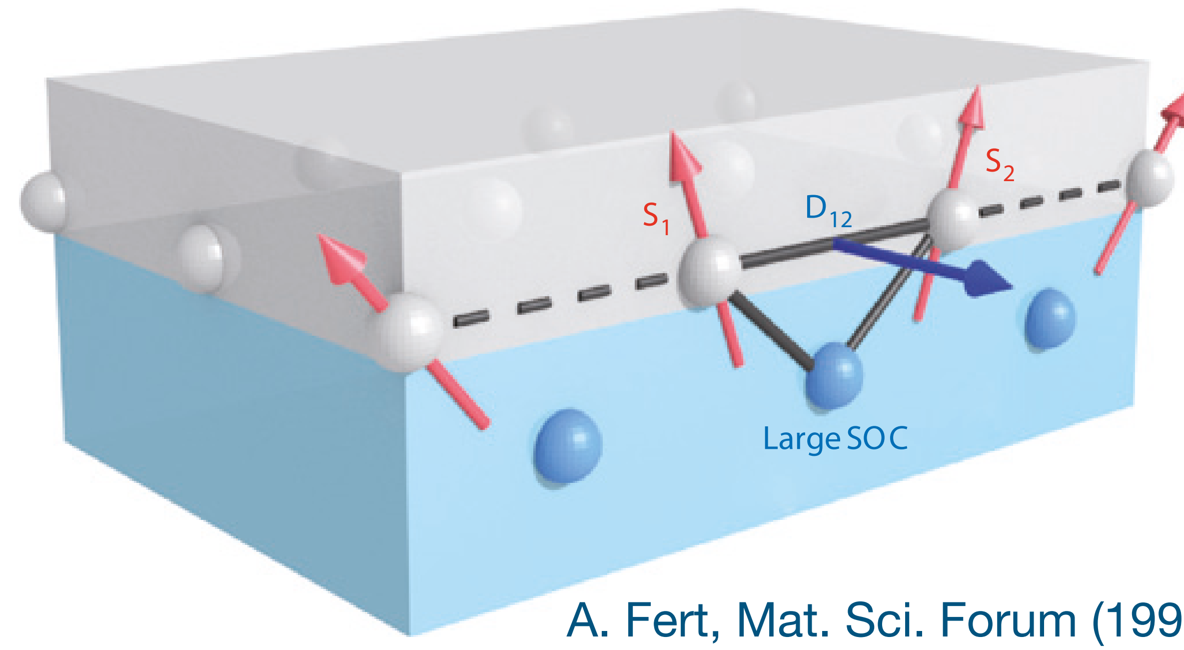
Dzyaloshinskii-Moriya in ultrathin films

Interface-driven chiral interaction in ultrathin ferromagnets on underlayers with strong **spin-orbit coupling (SOC)**

$$\mathcal{H}_{\mathrm{DM}} = -\vec{D}_{12} \cdot \left(\vec{S}_1 \times \vec{S}_2\right)$$

Chiral spin state ↑ → ↓ ←



A. Fert, Mat. Sci. Forum (1990)
A. Fert and P. M. Levy, PRL (1980)

Talks by Stefan Blügel and Mairbek Chshiev, Monday morning

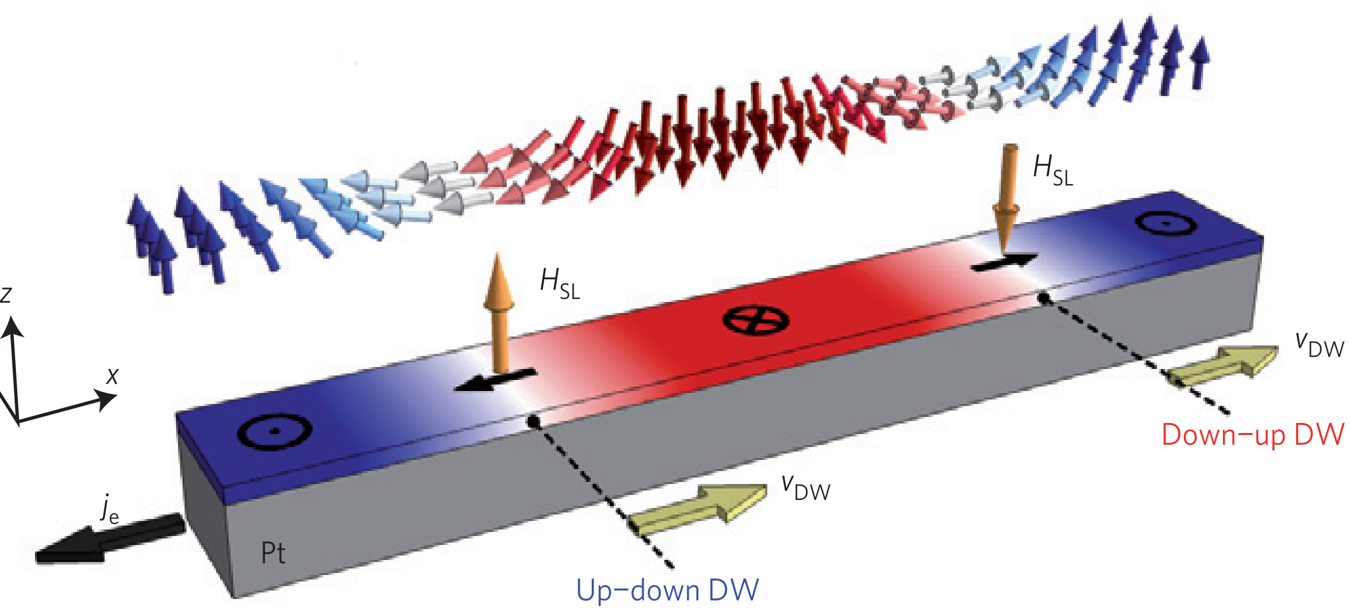
F ↑ ↑ ↑ ↑

AF ↑ ↓ ↑ ↓

$$\mathcal{H}_{\mathrm{ex}} = -J_{ij}\vec{S}_j \cdot \vec{S}_j$$

Some possible chiral spin textures

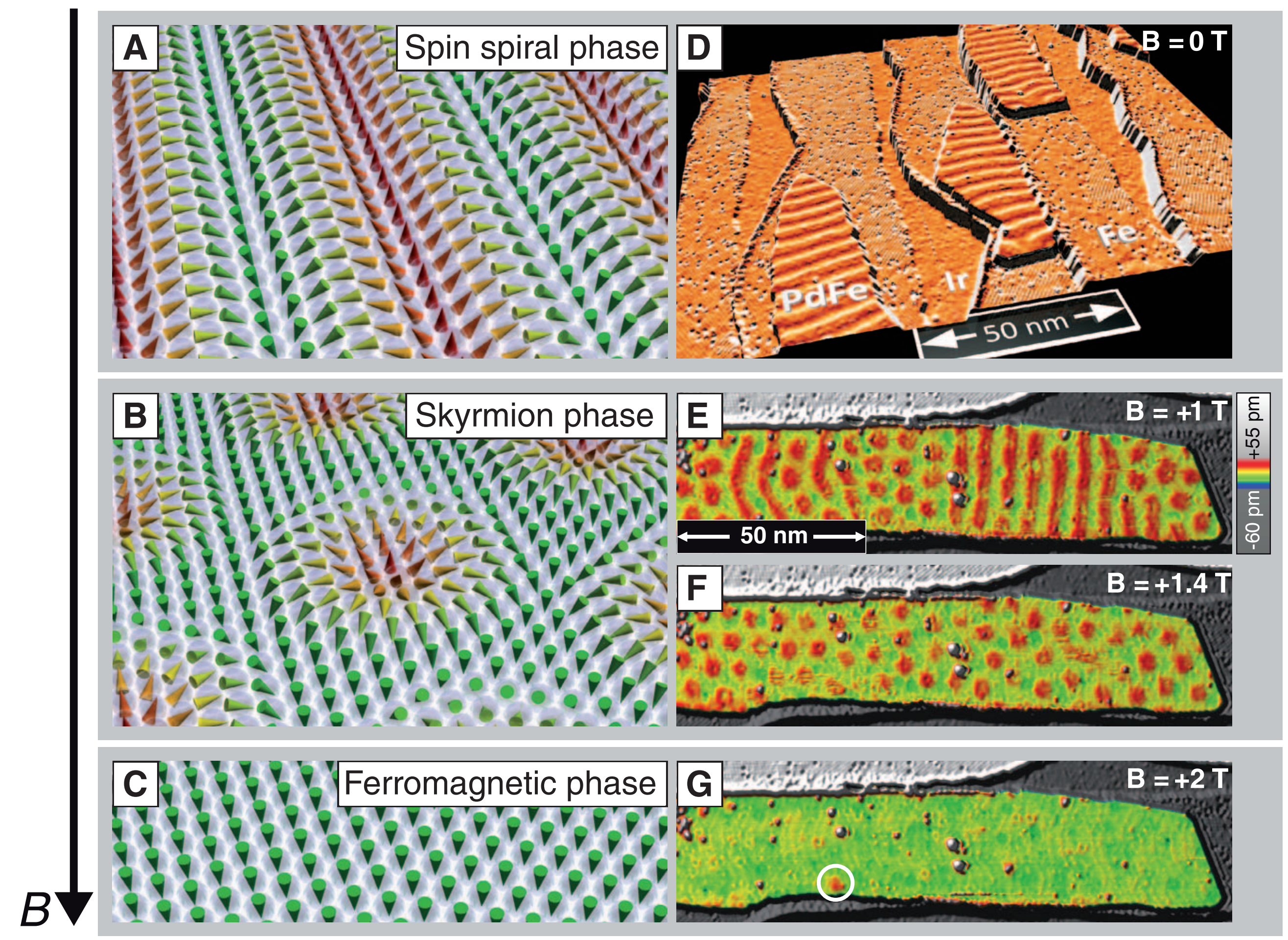
Homochiral (Néel) domain walls



S. Emori *et al*., Nat. Mater. **12**, 611 (2013)
K. Ryu *et al*., Nat. Nanotech. **8**, 527 (2013)
G. Chen *et al*., Nat. Commun. **4**, 267 (2013)

Talk by Geoffrey Beach this morning

Skyrmions



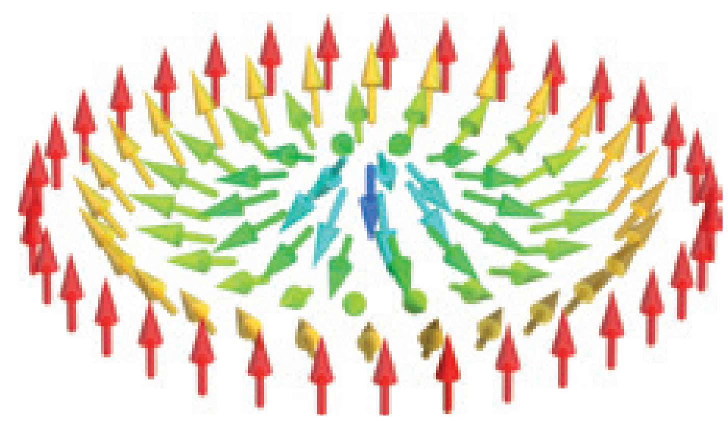
N. Romming *et al*., Science **341**, 636 (2013)
S. Heinze et al., Nat. Phys. **7**, 713 (2011)

Talk by Niklas Romming this morning

Possible application: A skyrmion racetrack?

A. Fert *et al.*, Nat. Nanotech. **8**, 152 (2013)
J. Iwasaki *et al*., Nat. Nanotechnol. **8**, 742 (2013)
J. Sampaio *et al*., Nat. Nanotech. **8**, 839 (2013)

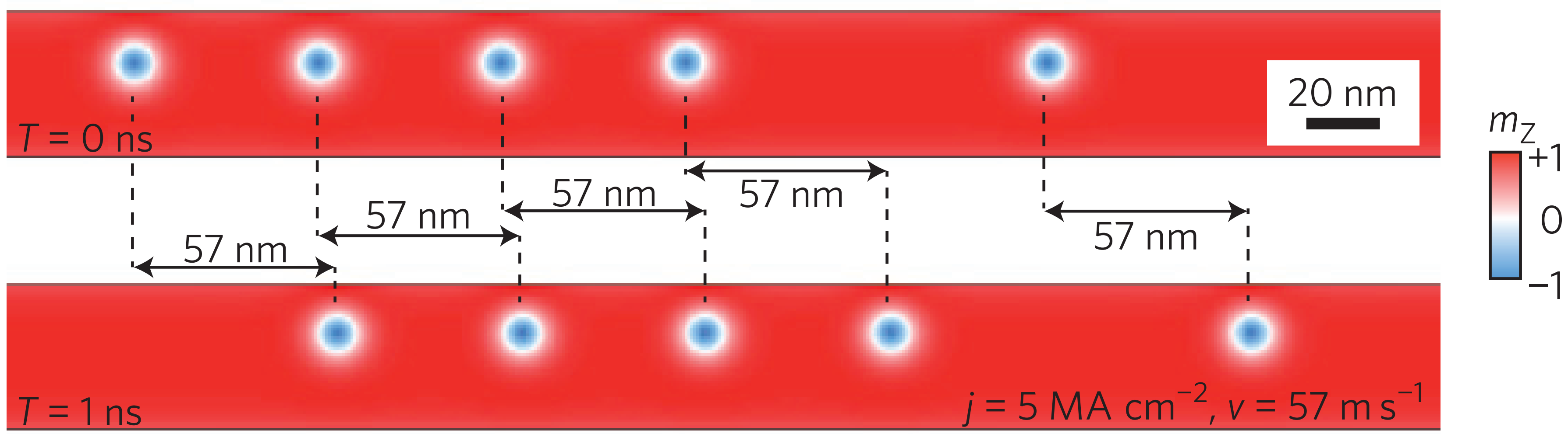
Talks by Naoto Nagaosa and Vincent Cros this morning



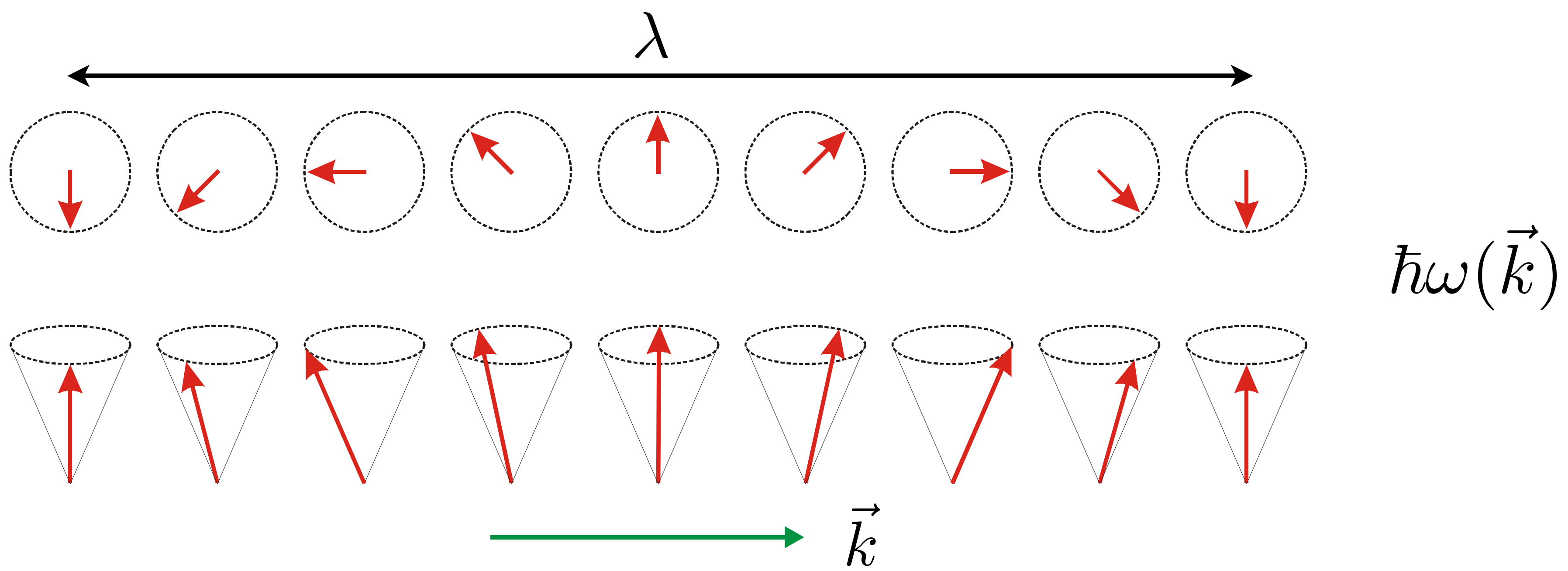
"Hedgehog" skyrmion

Weak pinning,
defects are avoided

Skyrmion chains
can be propagated
along track



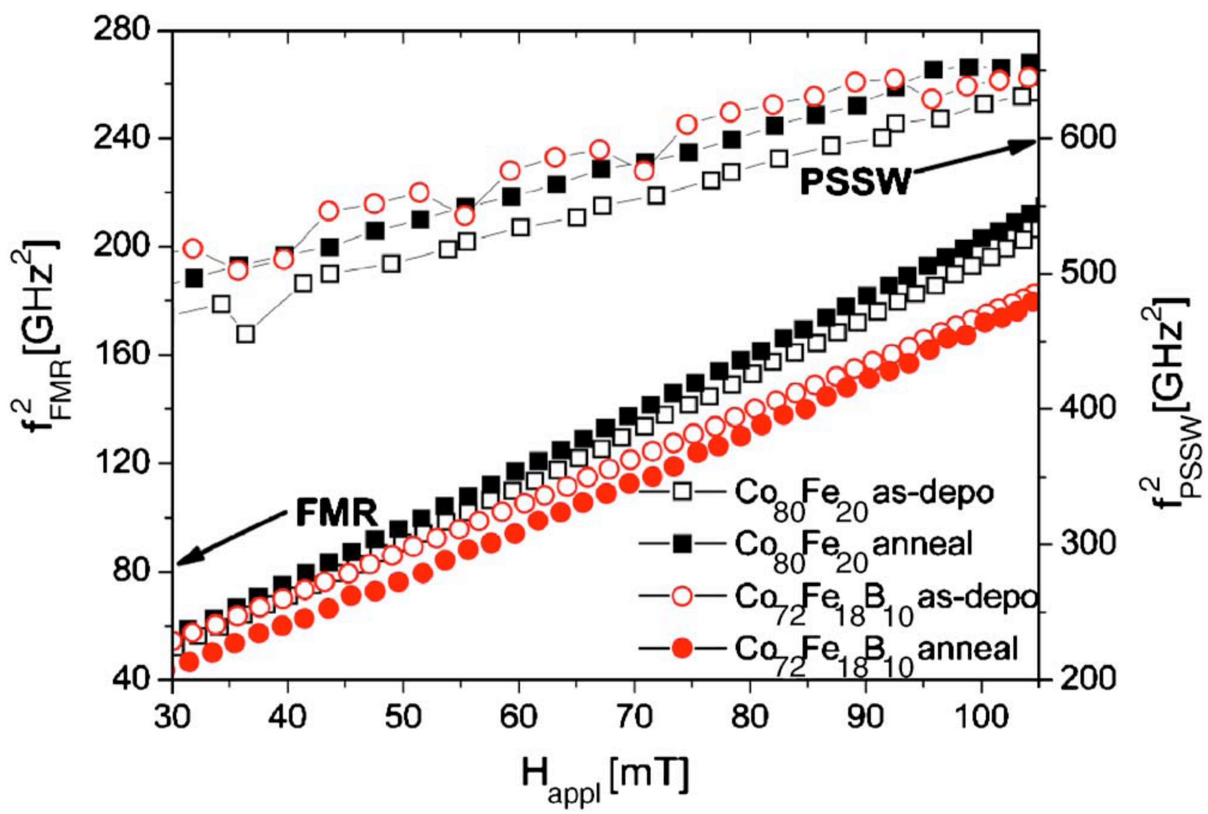
What about *spin waves*?

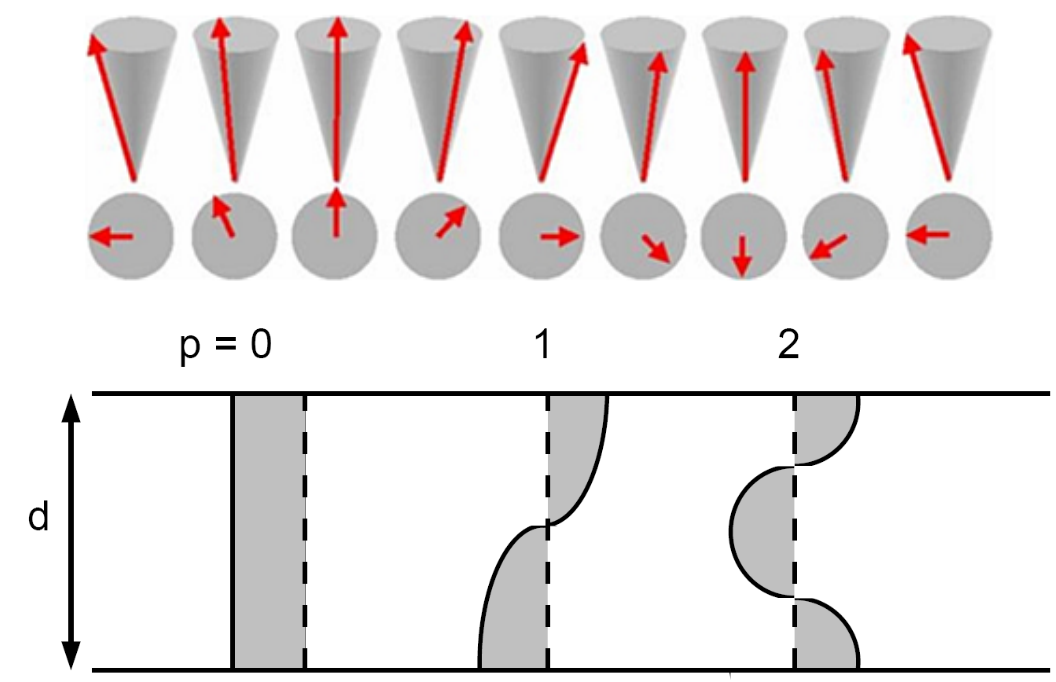


- Spin waves are elementary excitations of a magnetic system
- Quantized spin-wave: magnon (*cf* phonons for elastic waves)
- Dynamic response and low-temperature thermodynamics

Spin waves as probes of magnetic properties

- e.g., Determine exchange constant from frequencies of perpendicular standing spin waves (PSSW)



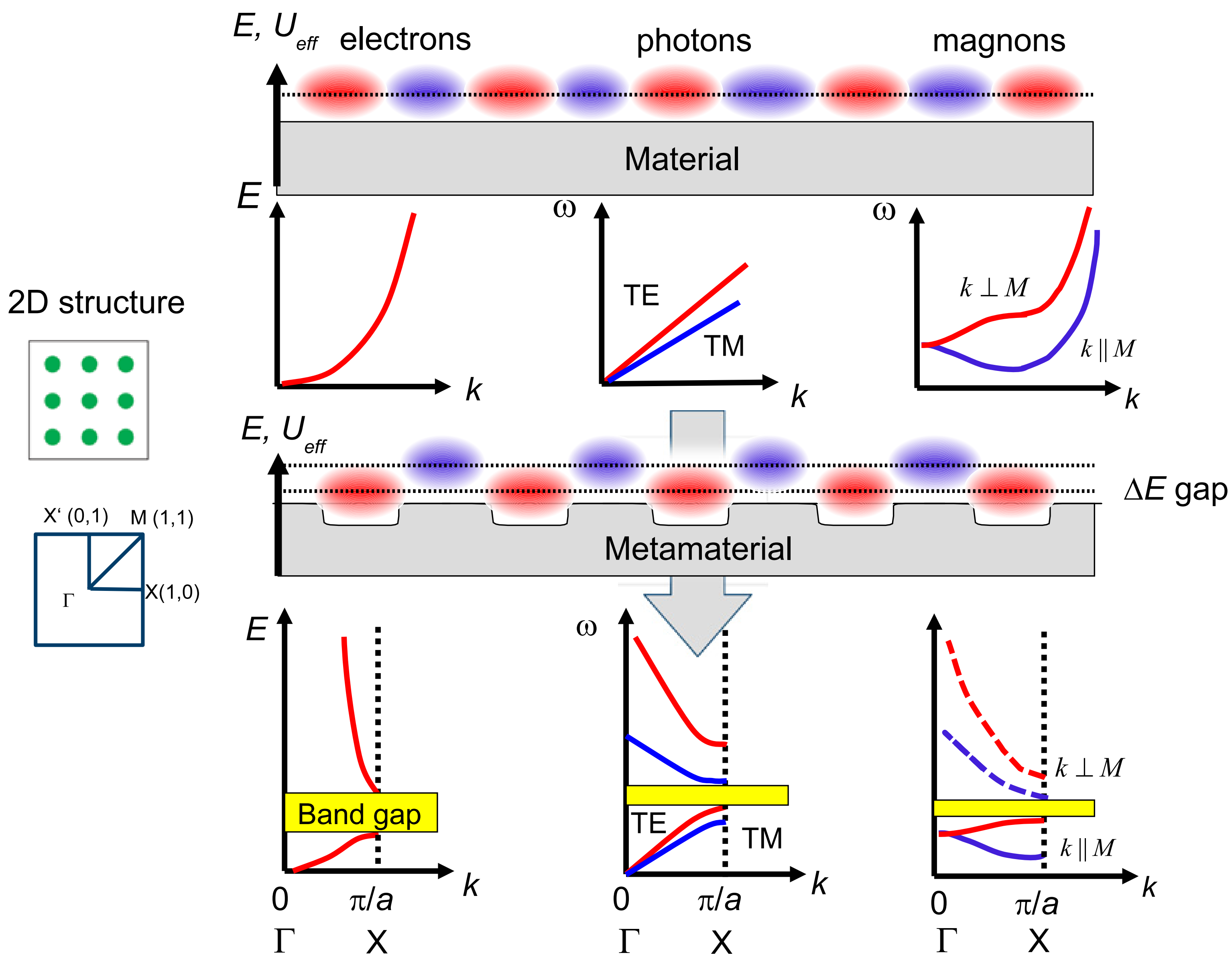


$$\omega_{\mathrm{PSSW}}^2 = \left[\omega_H + \omega_{\mathrm{eff}} + \gamma \frac{2A}{M_\mathrm{s}}\left(\frac{\pi p}{d}\right)^2\right]\left[\omega_H + \gamma \frac{2A}{M_\mathrm{s}}\left(\frac{\pi p}{d}\right)^2\right]$$

C. Bilzer, ..., JVK *et al*., J. Appl. Phys. **100**, 053903 (2008)

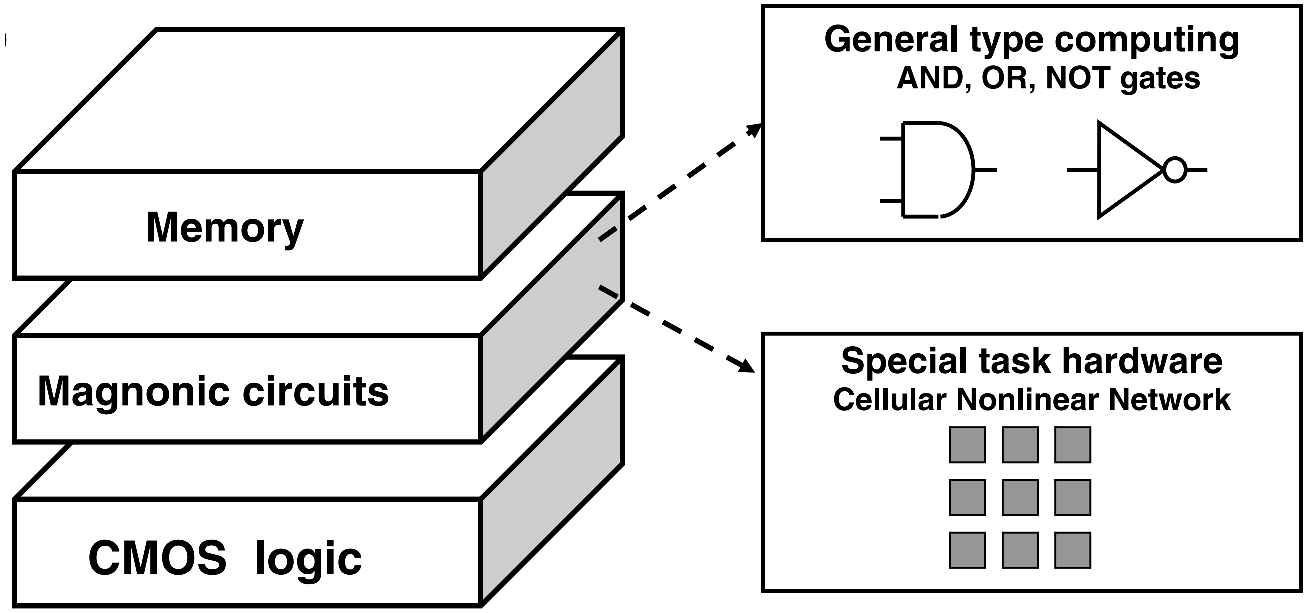
Spin waves as vectors of information processing

- **Magnonics**: Control of spin waves for information transfer and processing (*cf*. light for photonics)

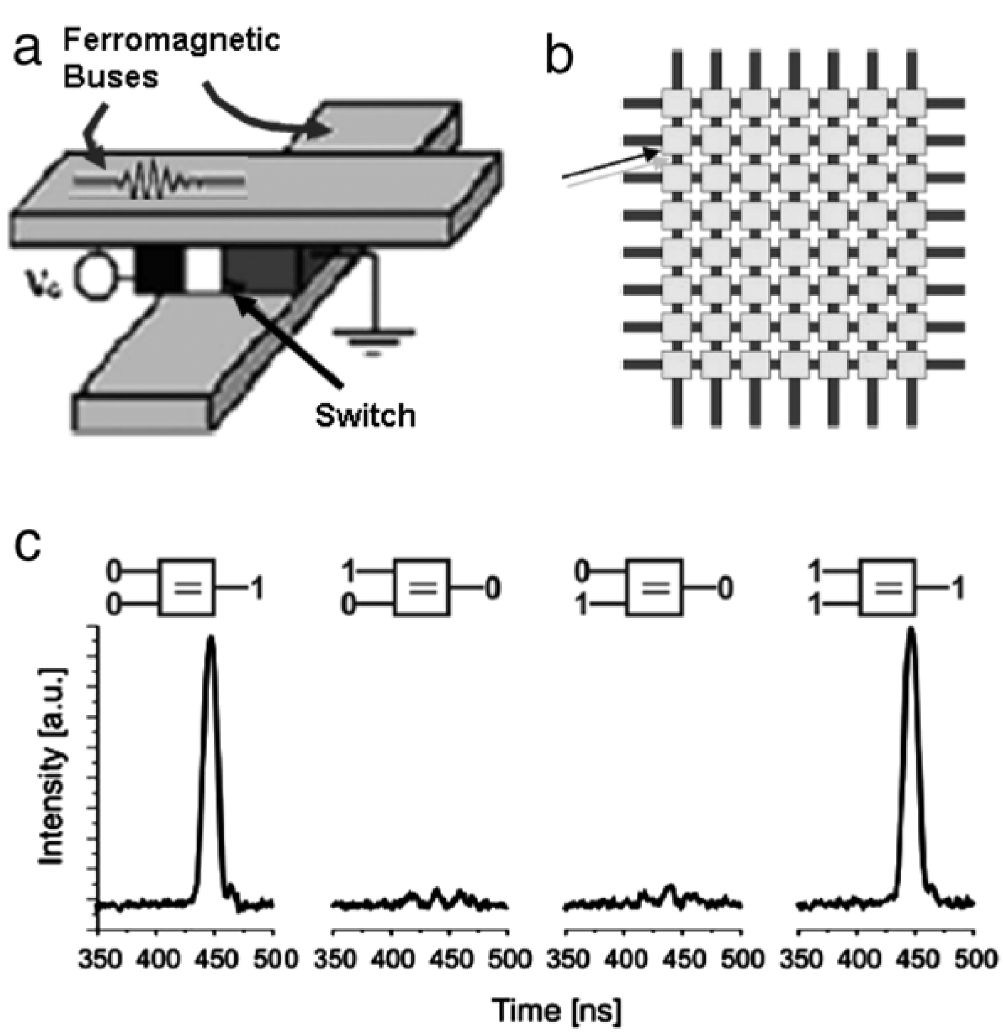


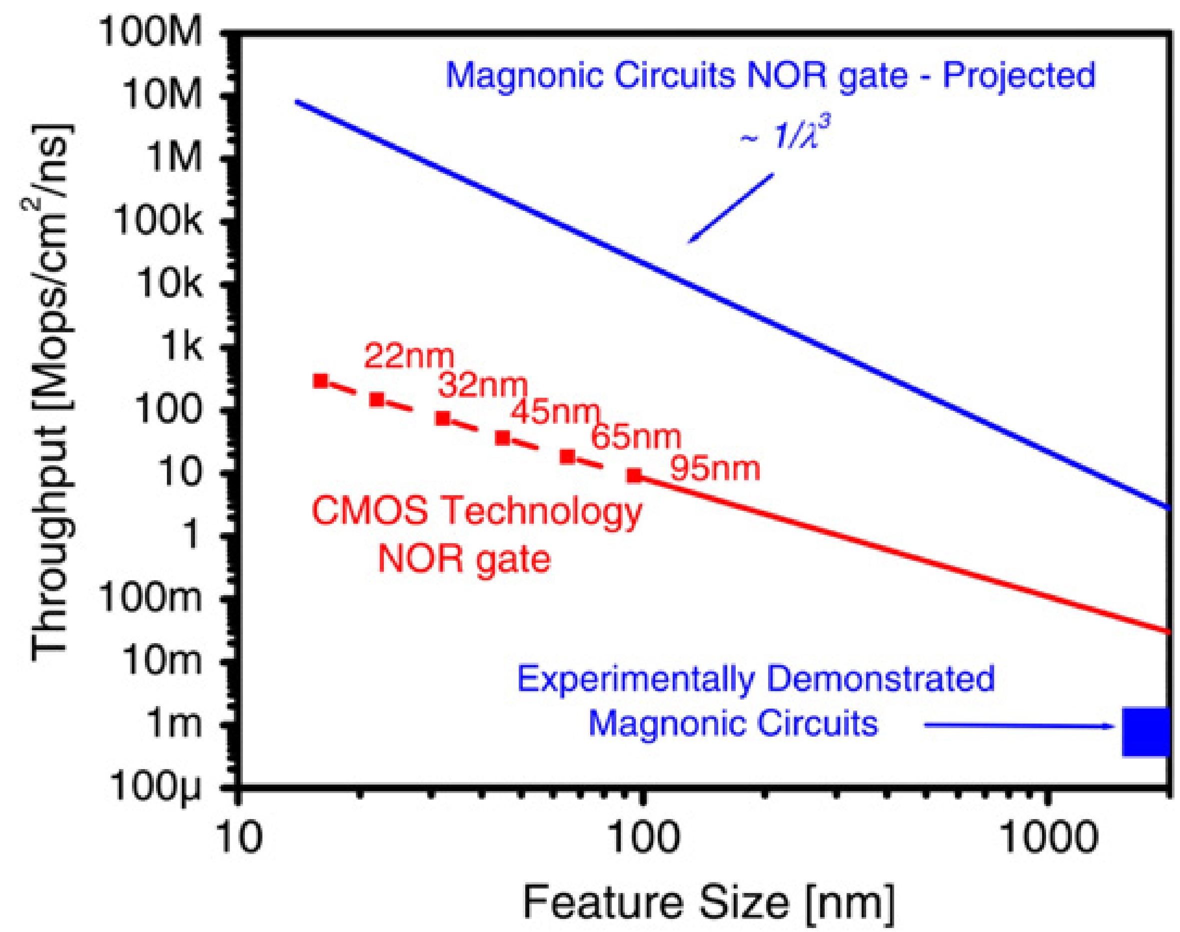
Example: Engineering band structures with metamaterials

B. Lenk *et al*., Phys. Rep. **507**, 107 (2011)



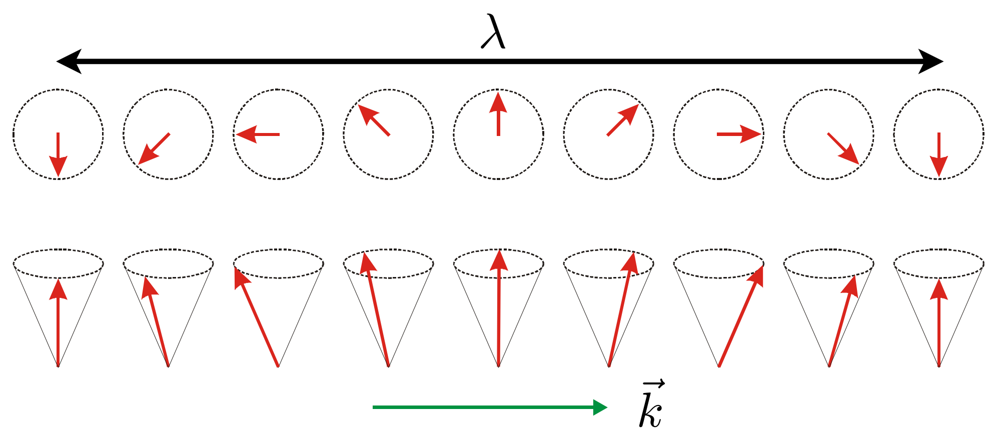
Example: Logic devices

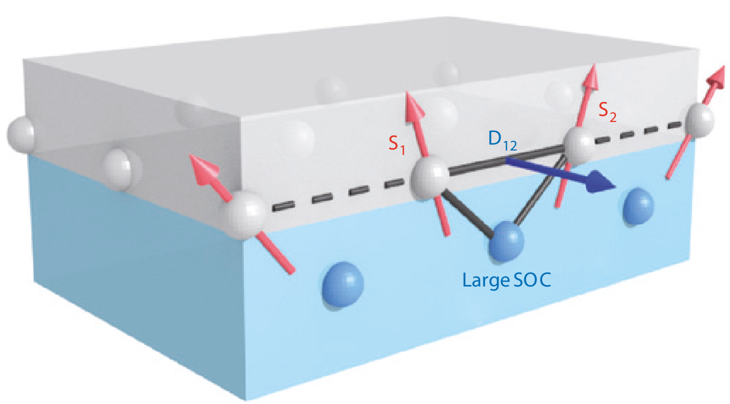


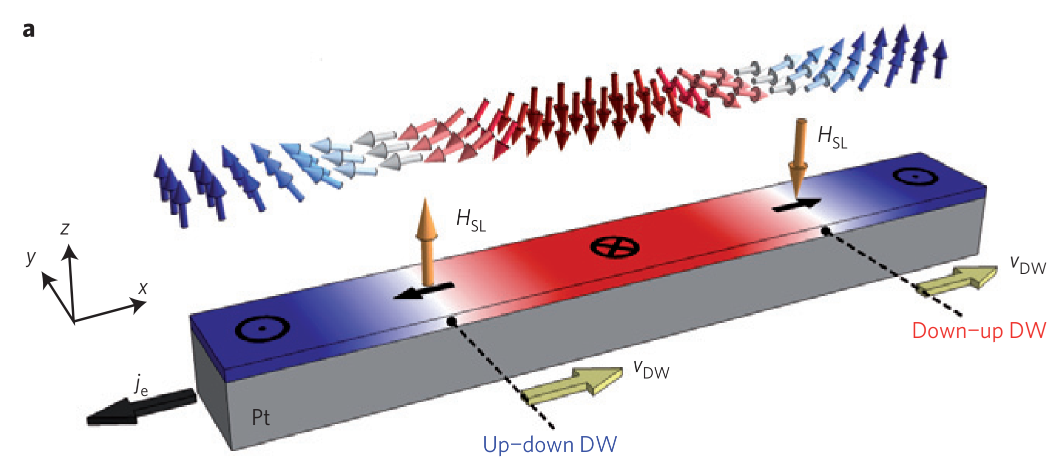


A. Khitun *et al*., J. Phys. D: Appl. Phys. **43**, 264005 (2010)
V. V. Kruglyak *et al*., J. Phys. D: Appl. Phys. **43**, 264001 (2010)

Today's talk: Spin waves in chiral spin textures







Probe strength of the Dzyaloshinskii-Moriya interaction in ultrathin films

Nonreciprocal propagation and *channelling* effects in spin textures

Talk outline

- Part 1: Brief overview of chiral interactions and spin waves
- Part 2: Spin wave channelling in chiral walls
  - *Nonreciprocal propagation along Néel walls*
  - *Curved magnonic waveguides*
- Part 3: Edge modes in nanostructures
  - *Tilted spin states at dot edges*
- Part 4: Brillouin light spectroscopy measurements
  - *Pt/Co/AlOx, [W, Hf]/CoFeB/MgO*

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Calculating spin wave spectra

- First, need to determine equilibrium ground state of spin configuration
- Use continuum approximation (micromagnetics) $\|\mathbf{m}(\mathbf{r},t)\| = 1$

$$U_{\mathrm{ex}} = \int dV\, A\, (\nabla \mathbf{m})^2$$

Exchange

$$U_K = -\int dV\; K_u\, (\mathbf{m}\cdot\hat{\mathbf{z}})^2$$

Uniaxial anisotropy

$$U_{\mathrm{d}} = \frac{1}{2}\mu_0 M_s \int dV\, \mathbf{m}\cdot\mathbf{H}_d$$

$$\mathbf{H}_d(\mathbf{r}) = -\nabla\Phi_M(\mathbf{r})$$

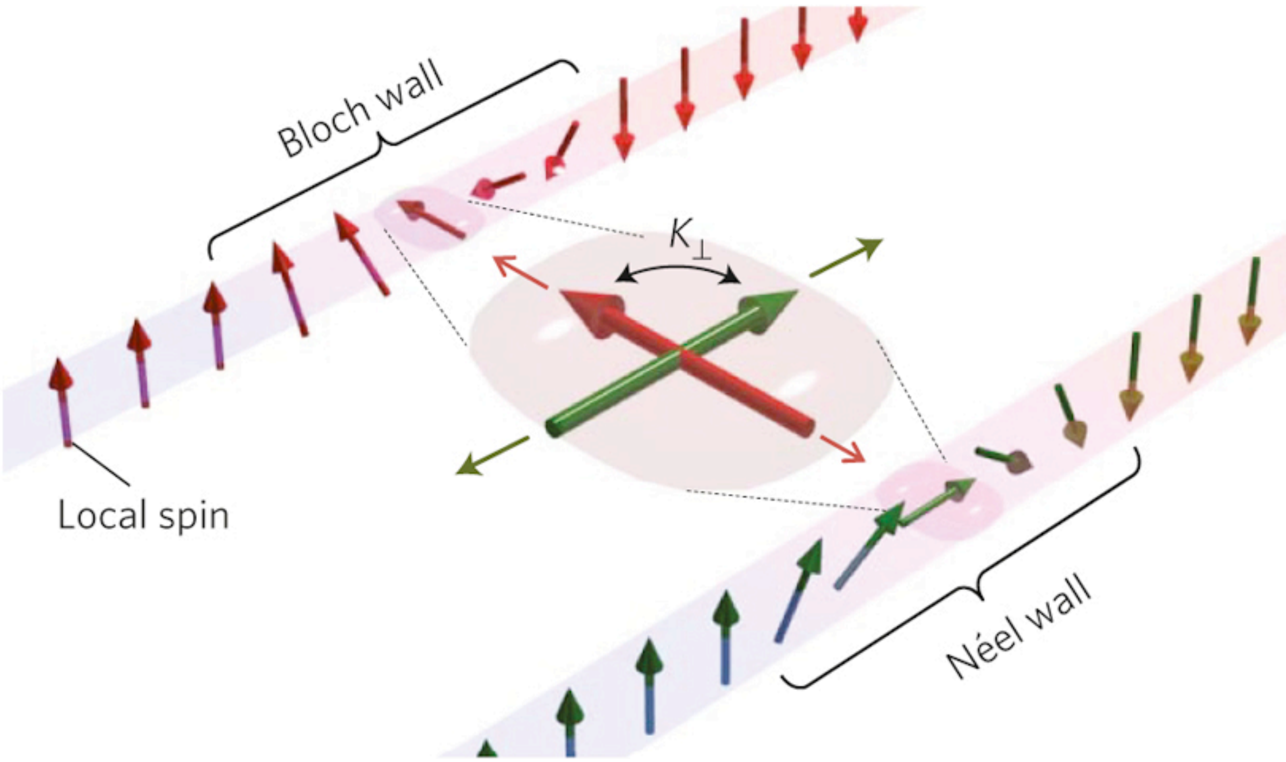
$$\Phi_M(\mathbf{r}) = \frac{M_s}{4\pi}\left[\int dV' \frac{\nabla\cdot\mathbf{m}}{\|\mathbf{r}-\mathbf{r}'\|} + \int dS' \frac{\mathbf{m}\cdot\hat{\mathbf{n}}}{\|\mathbf{r}-\mathbf{r}'\|}\right]$$

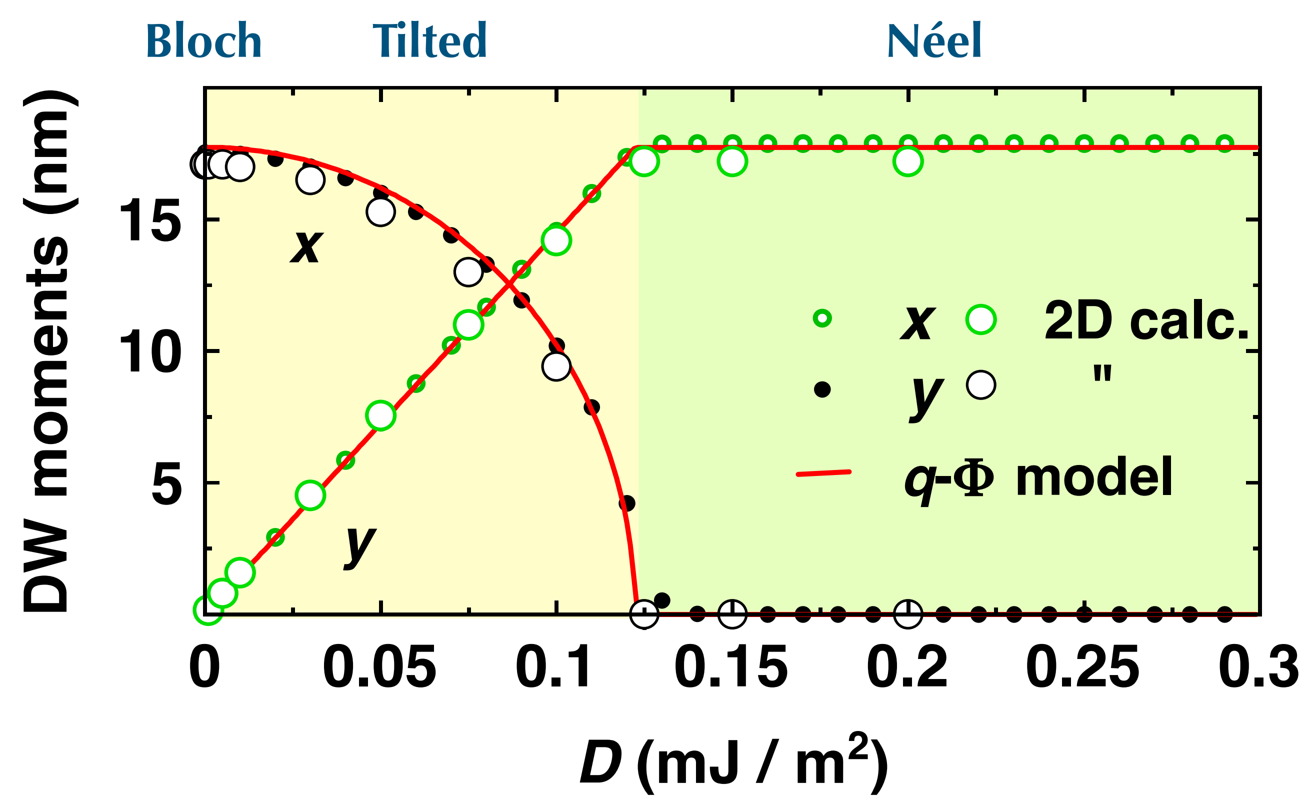
Dipole-dipole

$$U_{\mathrm{DM}} = \int dV\, D\left[m_z\,(\nabla\cdot\mathbf{m}) - (\mathbf{m}\cdot\nabla)\,m_z\right]$$

Dzyaloshinskii-Moriya

- <u>Example</u>: (Homochiral) Néel domain walls are preferred ground state if DMI sufficiently large to overcome volume dipole interaction





$$\sigma_w = 4\sqrt{AK_0} - \pi D$$

Néel domain wall energy

A. Thiaville *et al*., Europhys. Lett. **100**, 57002 (2012)
M. Heide *et al*., Phys. Rev. B **78**, 140403 (2008)

Calculating spin wave spectra

- Second, compute fluctuations about ground state
- Linearize equations of motion

$$\mathbf{m}(\mathbf{r},t) = \underbrace{\mathbf{m}_0(\mathbf{r})}_{\text{equilibrium component}} + \underbrace{\delta\mathbf{m}(\mathbf{r},t)}_{\text{fluctuations}}$$

$$\frac{\partial \delta\mathbf{m}}{\partial t} = -\gamma_0 \left[\delta\mathbf{m}(t) \times \mathbf{H}_{\text{eff}} + \mathbf{m}_0 \times \delta\mathbf{H}_{\text{eff}}(t)\right]$$

linearized torque equation

$$\mathbf{H}_{\text{eff}} = -\frac{1}{\mu_0 M_s}\frac{\delta U}{\delta\mathbf{m}}$$

effective field

- Solve analytically (special cases) or numerically with micromagnetics simulations

Modified “Winter” modes - Perturbation theory

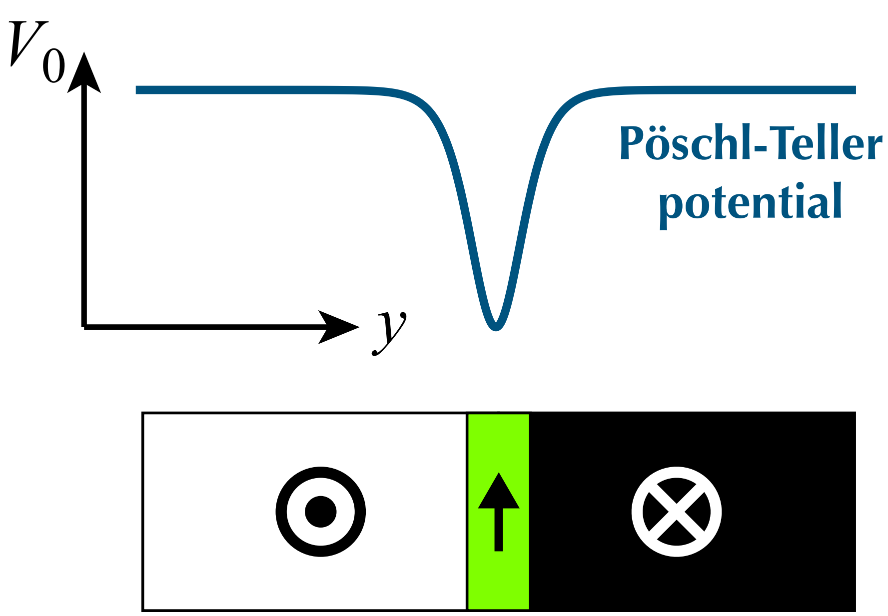
- Bloch wall (“Winter”) spin wave eigenmodes are solutions to Schrödinger-like equation with reflectionless potential

$$\mathbf{m} = (\sin\theta\cos\phi, \sin\theta\sin\phi, \cos\theta)$$

$$\lambda = \sqrt{\frac{A}{K_0}}$$

$$\left[-\lambda^2\nabla^2 + \boxed{1 - 2\,\mathrm{sech}^2\left(\frac{y}{\lambda}\right)}\right]\delta\phi(\vec{r}) = \Lambda_\phi \delta\phi(\vec{r})$$

$$\left[-\lambda^2\nabla^2 + \boxed{1 - 2\,\mathrm{sech}^2\left(\frac{y}{\lambda}\right) + \kappa}\right]\delta\theta(\vec{r}) = \Lambda_\theta \delta\theta(\vec{r})$$



$|\xi_{k_\alpha,k_\beta}\rangle$

J. M. Winter, Phys. Rev. **124**, 452 (1961)

- DMI leads to scattering between Winter modes

$$\left[-\lambda^2\nabla^2 + 1 - 2\,\mathrm{sech}^2\left(\frac{y}{\lambda}\right)\right]\delta\phi(\vec{r}) = \Lambda_\phi \delta\phi(\vec{r})$$

$$\left[-\lambda^2\nabla^2 + 1 - 2\,\mathrm{sech}^2\left(\frac{y}{\lambda}\right) + \kappa + \frac{D}{\sqrt{AK_0}}\mathrm{sech}\left(\frac{y}{\lambda}\right)\right]\delta\theta(\vec{r}) = \Lambda_\theta \delta\theta(\vec{r})$$

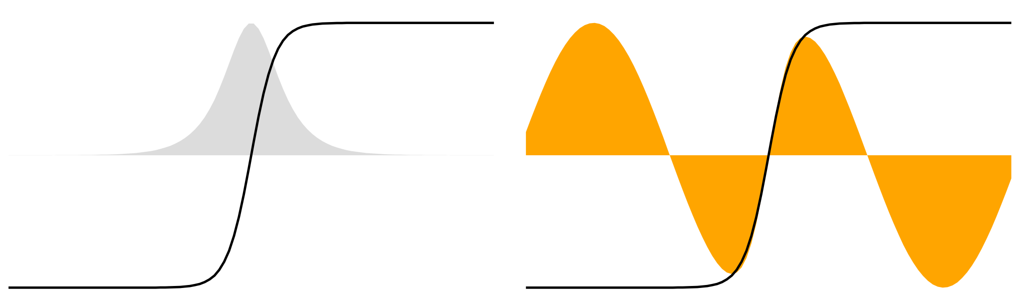
- Treat DMI as perturbation, calculate energy shifts using known eigenfunctions

$$-\langle \xi_{k_\alpha,k_\beta} | D\,\mathrm{sech}\,(y/\lambda)\,|\xi_{k_\alpha,k_\beta}\rangle$$

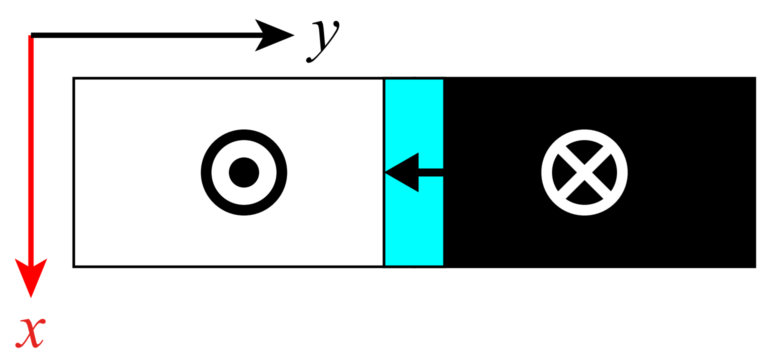
$$\langle \xi_{k_\alpha,k_\beta} | D\,\mathrm{sech}\,(y/\lambda)\,\frac{\partial}{\partial x}|\xi_{k_\alpha,k_\beta}\rangle$$

Matrix elements involved

$|\xi_{k_\alpha,k_\beta}\rangle$

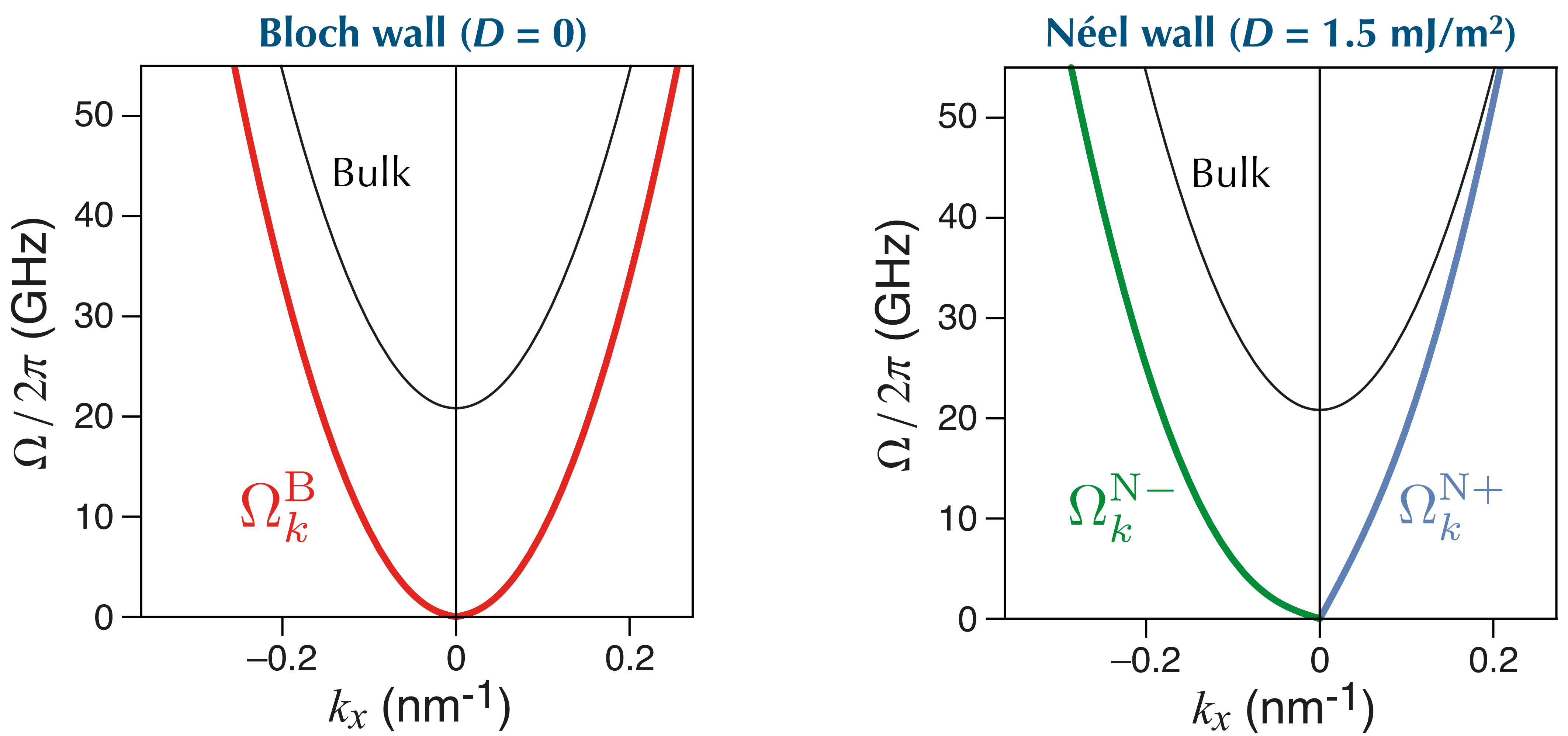


F. Garcia-Sanchez, ... , JVK, Phys. Rev. Lett. (19 June 2015)

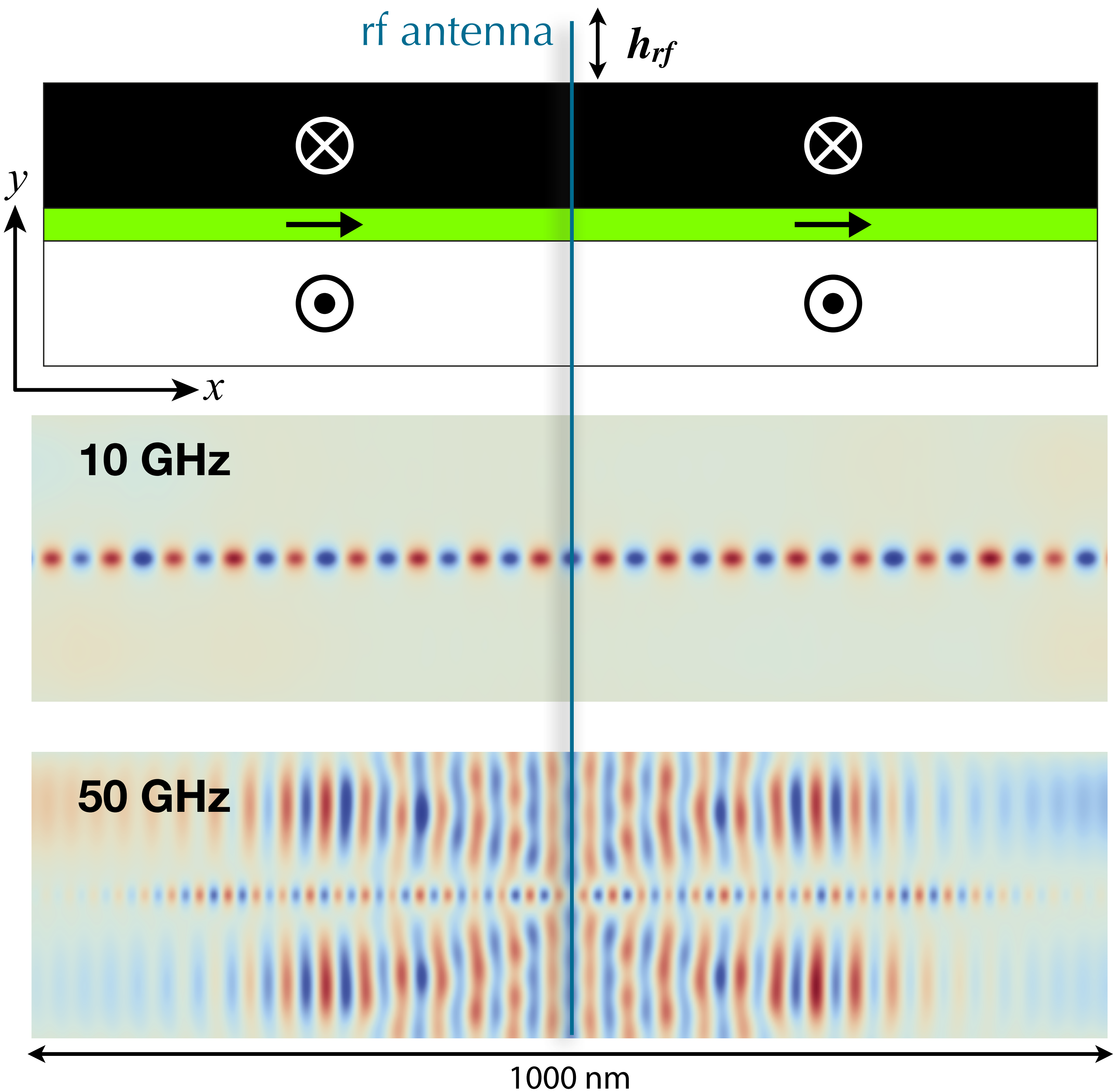


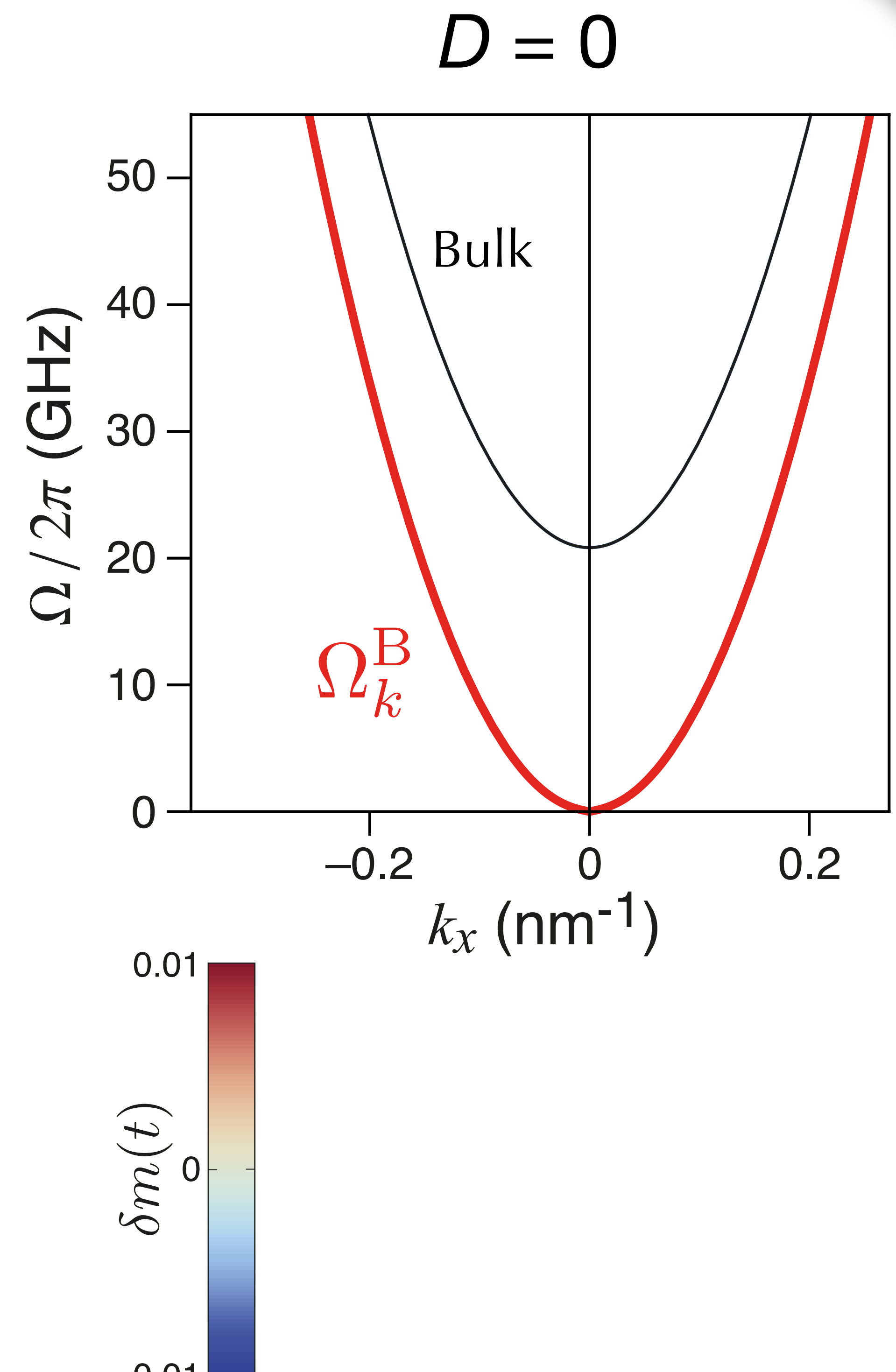
Nonreciprocal propagation *along* domain wall ($k_x \neq 0$, $k_y = 0$)

$$\Omega_k = \gamma \sqrt{\frac{2A}{\mu_0 M_s} k_x^2 \left(\frac{2A}{\mu_0 M_s} k_x^2 - \mu_0 H_\perp + \frac{\pi D}{2 M_s \lambda} \right)} + \frac{\pi \gamma D}{2 M_s} k_x$$

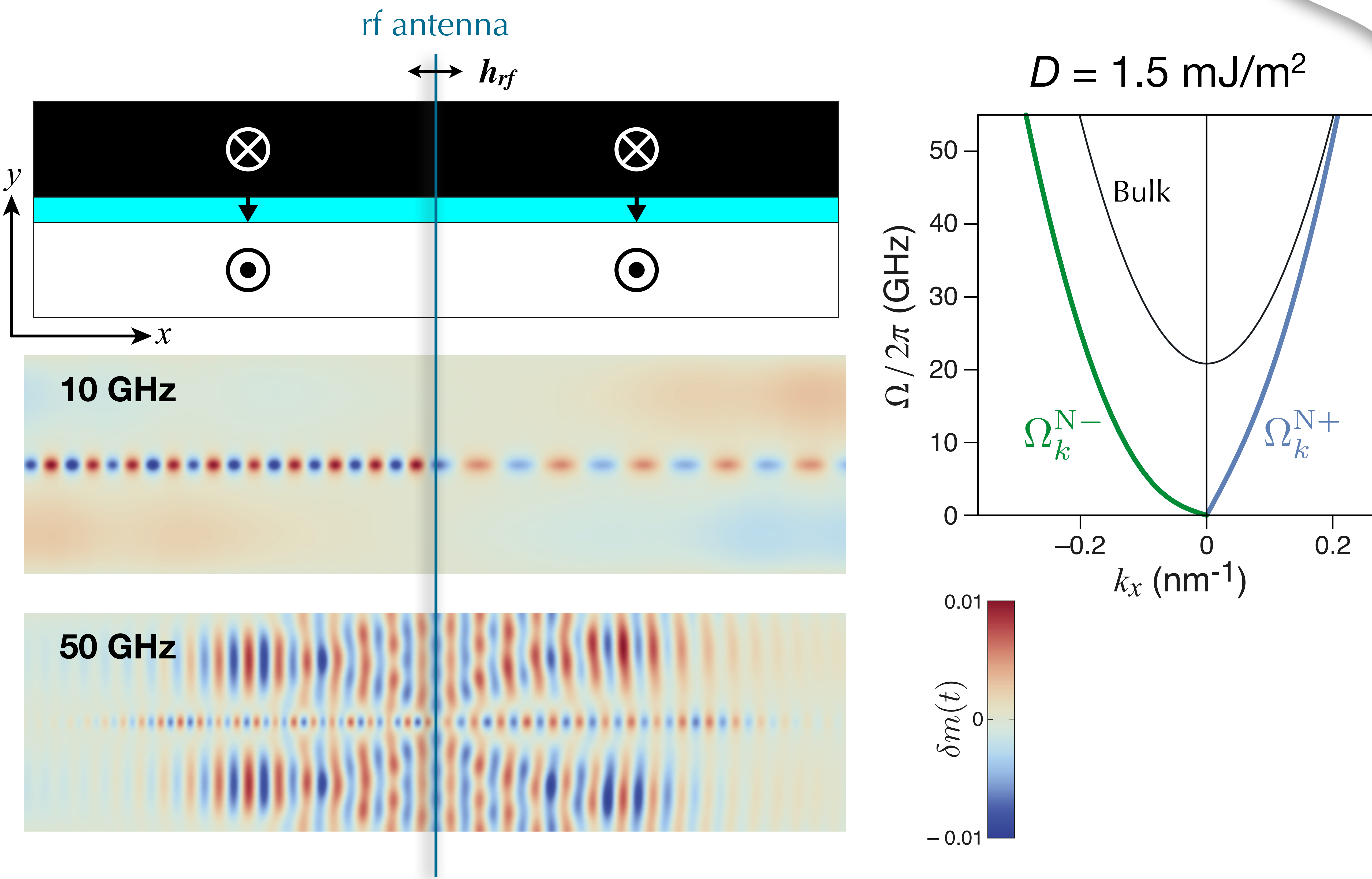


Channelling along Bloch walls

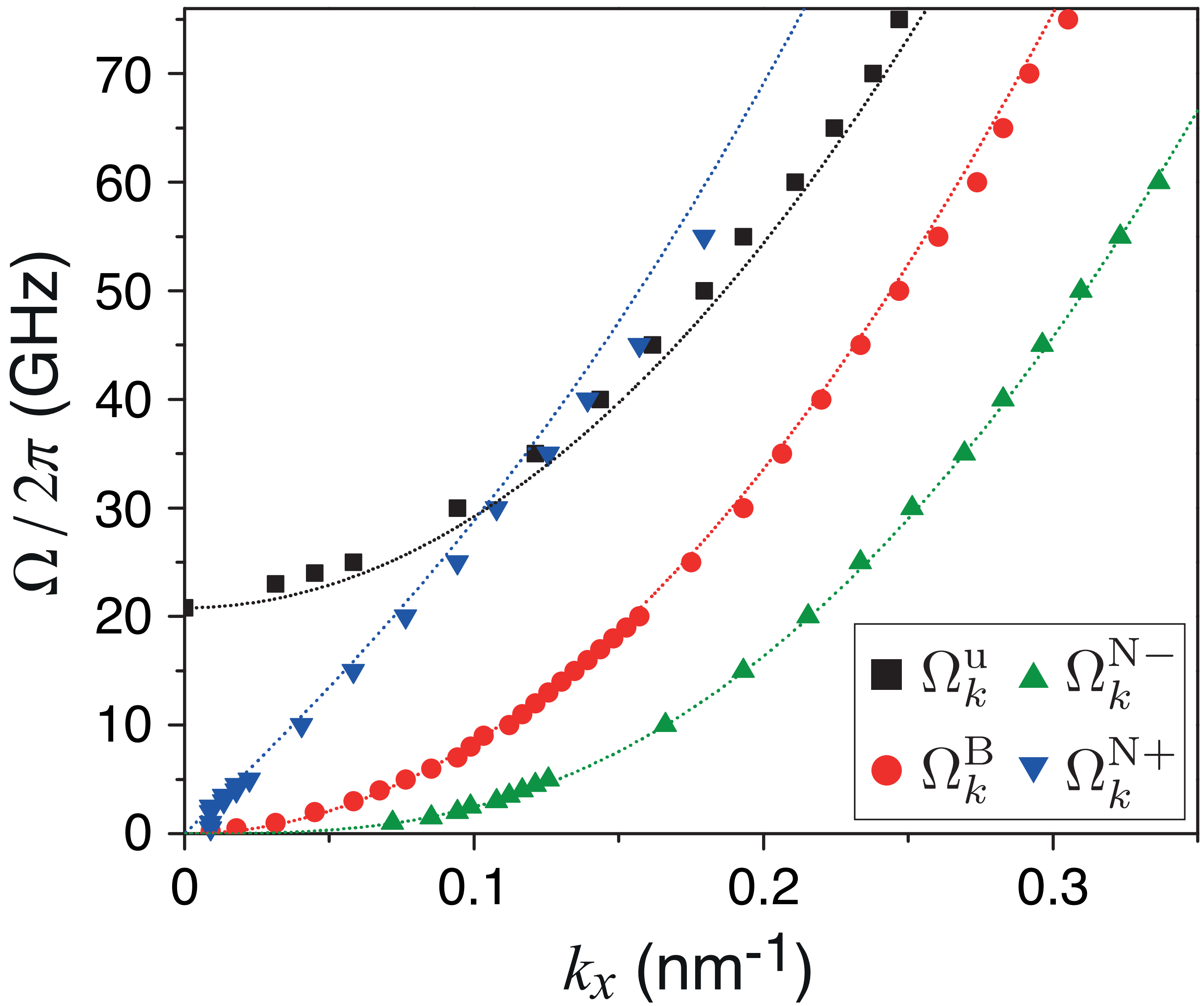




Asymmetric channelling along Néel walls

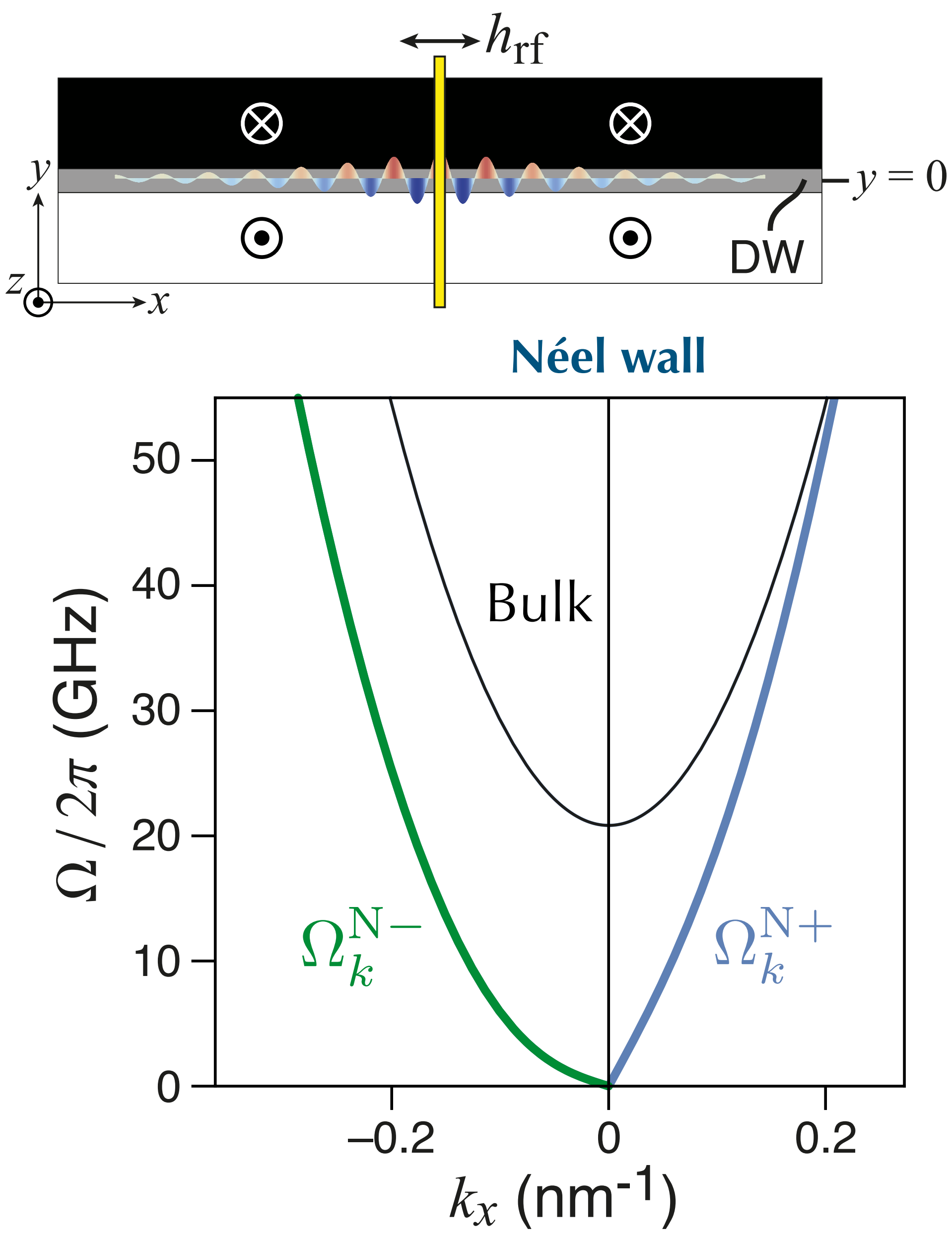


$$\Omega_k = \gamma\sqrt{\frac{2A}{\mu_0 M_s}k_x^2\left(\frac{2A}{\mu_0 M_s}k_x^2 - \mu_0 H_\perp + \frac{\pi D}{2M_s\lambda}\right)} + \frac{\pi\gamma D}{2M_s}k_x$$

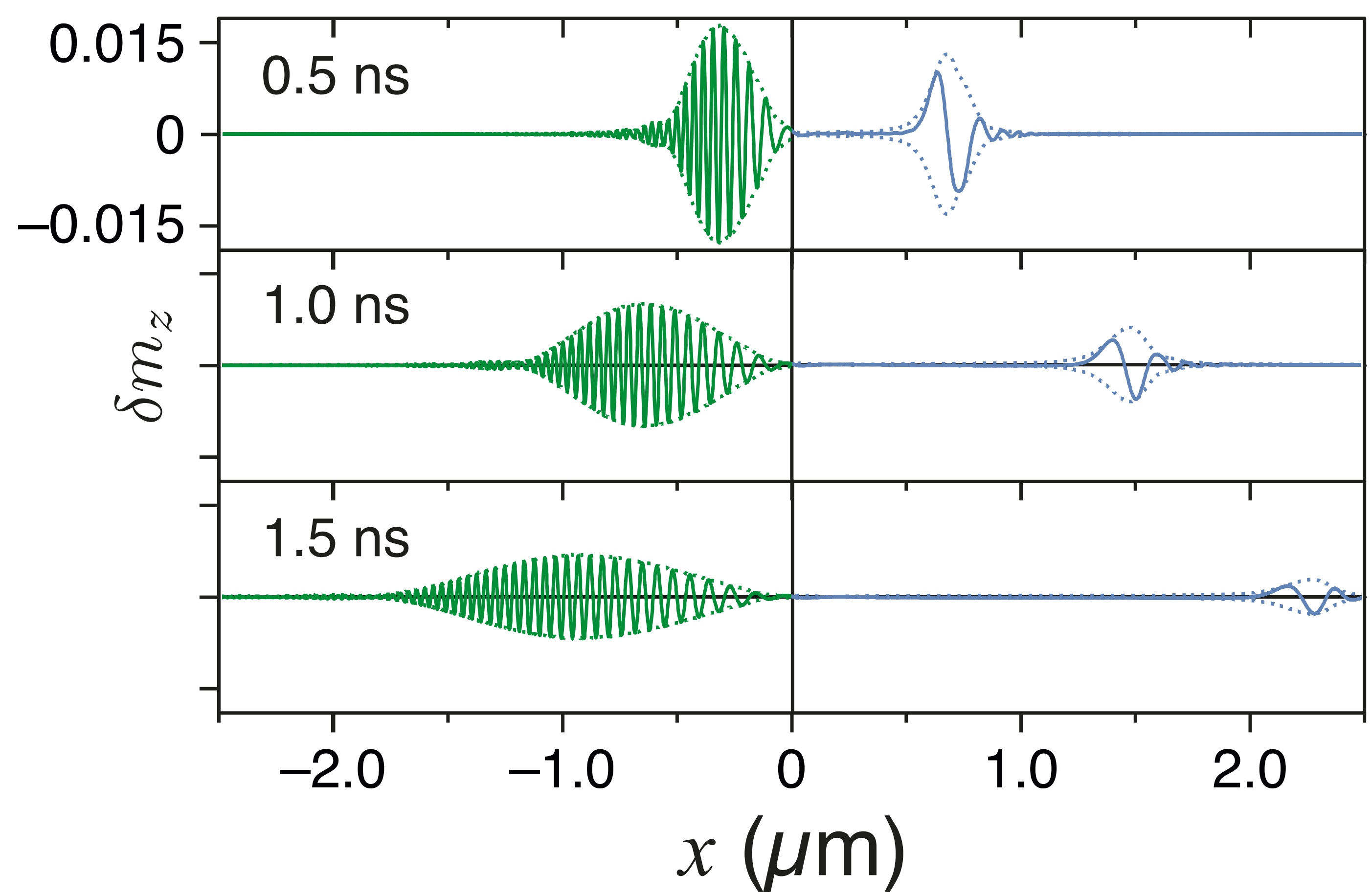


Good agreement between theory and simulation

Dynamics of channeled wave packets

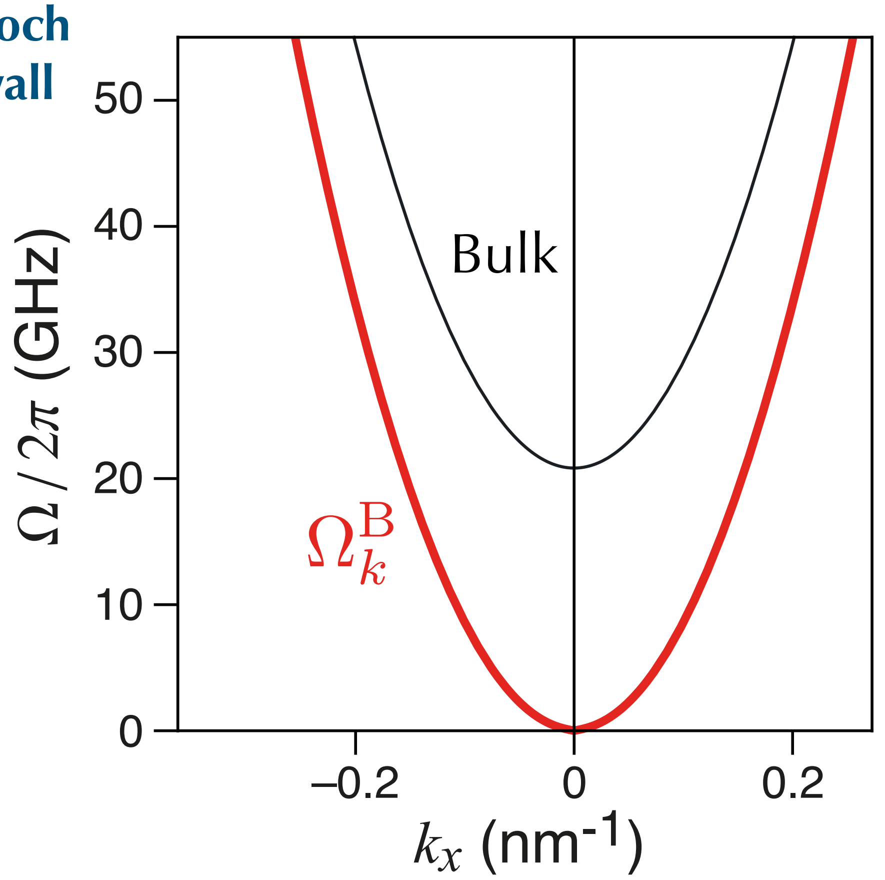


Dispersion is weaker along one propagation direction in Néel walls

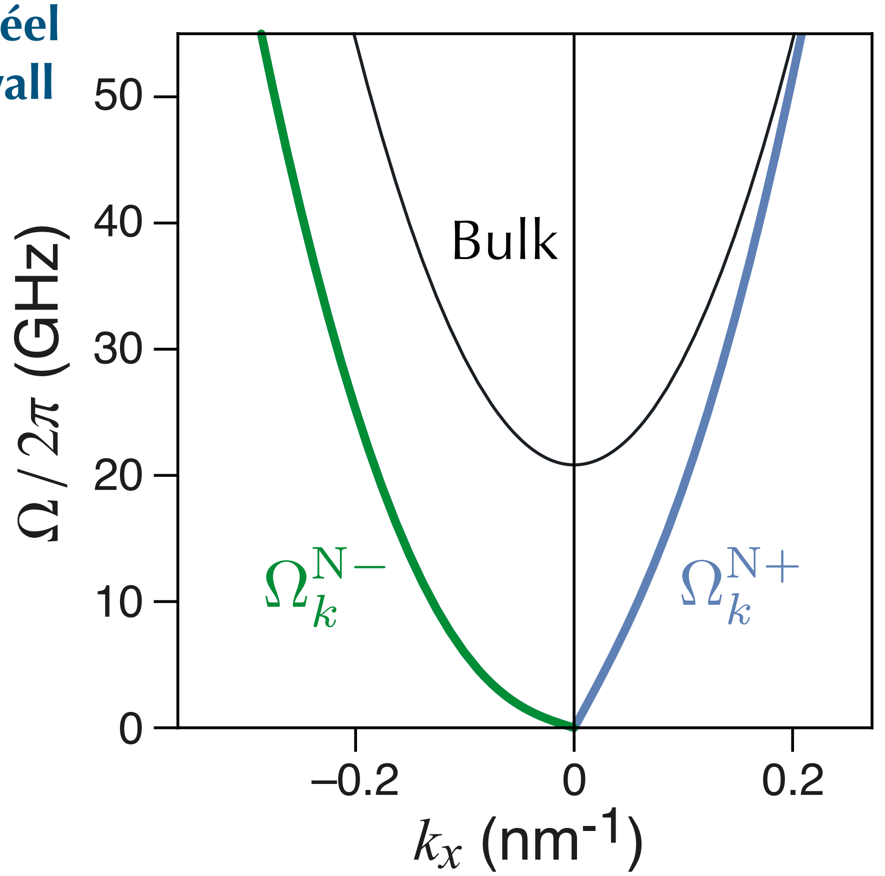


F. Garcia-Sanchez, ... , JVK, Phys. Rev. Lett. (19 June 2015)

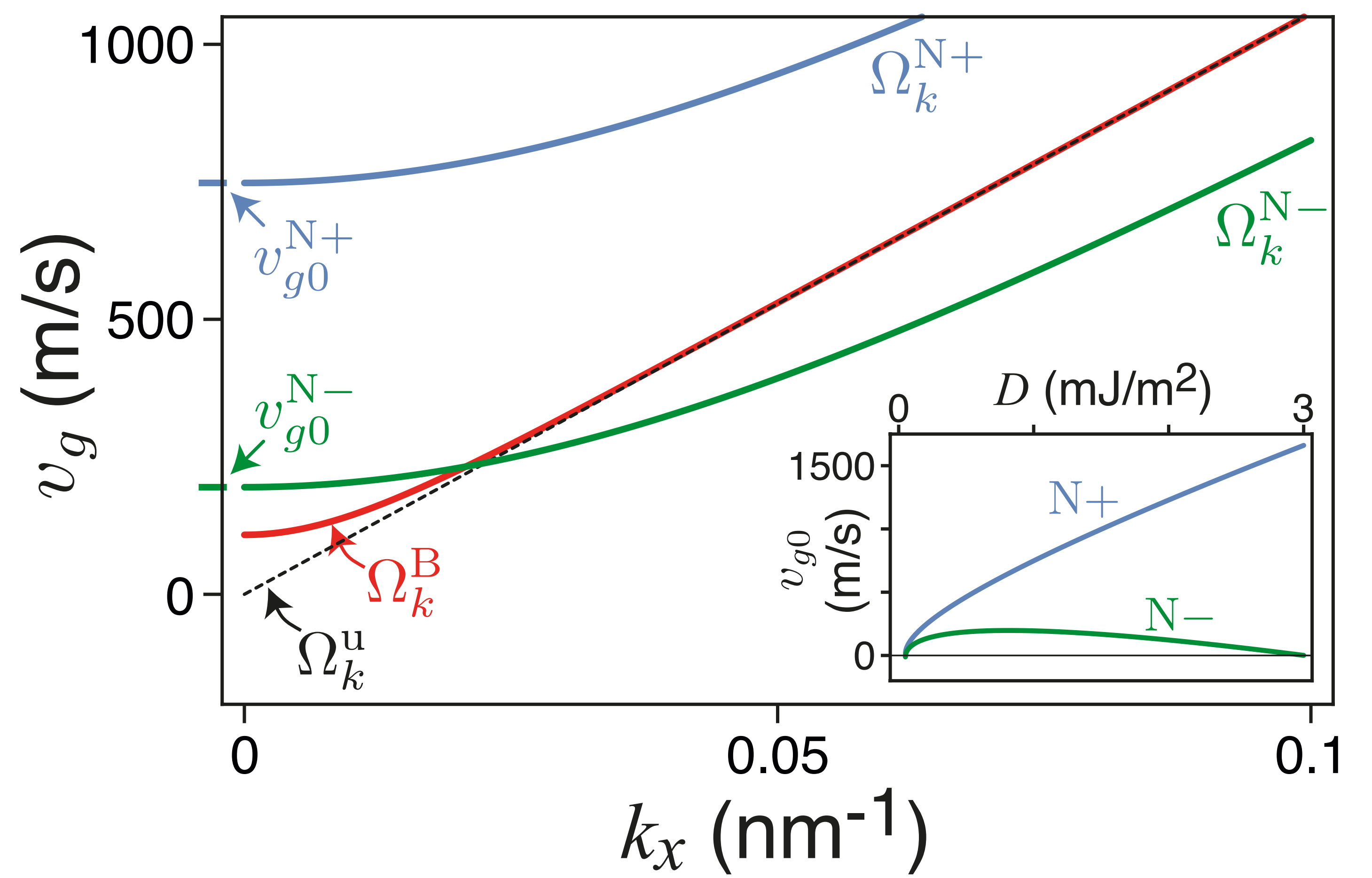
Bloch wall



Néel wall

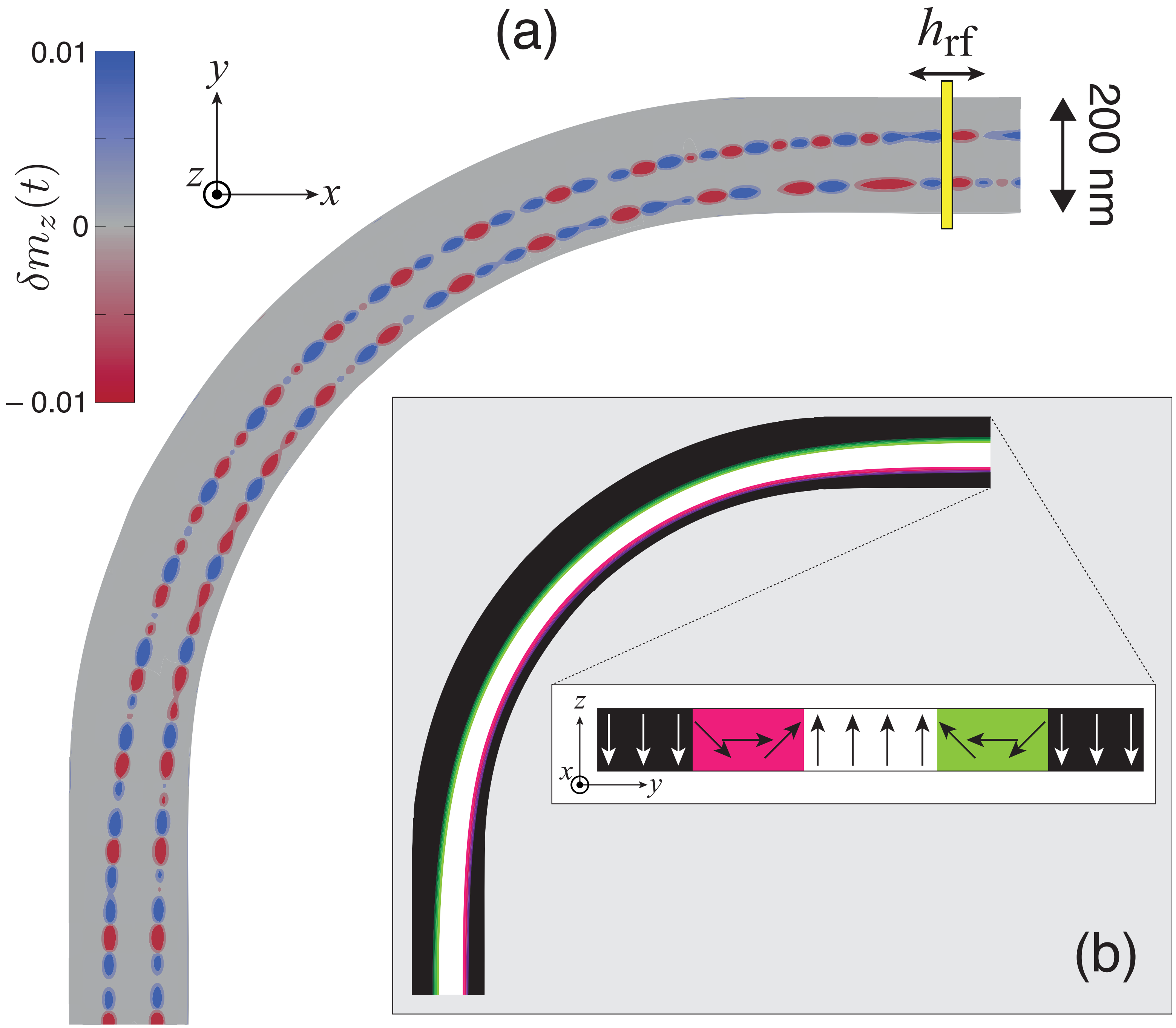


High group velocities for channeled spin waves along Néel walls



F. Garcia-Sanchez, ... , JVK, Phys. Rev. Lett. (19 June 2015)

Domain walls as curved magnonic waveguides



Magnons can propagate along the domain walls in curved geometries

F. Garcia-Sanchez, ... , JVK, Phys. Rev. Lett. (19 June 2015)

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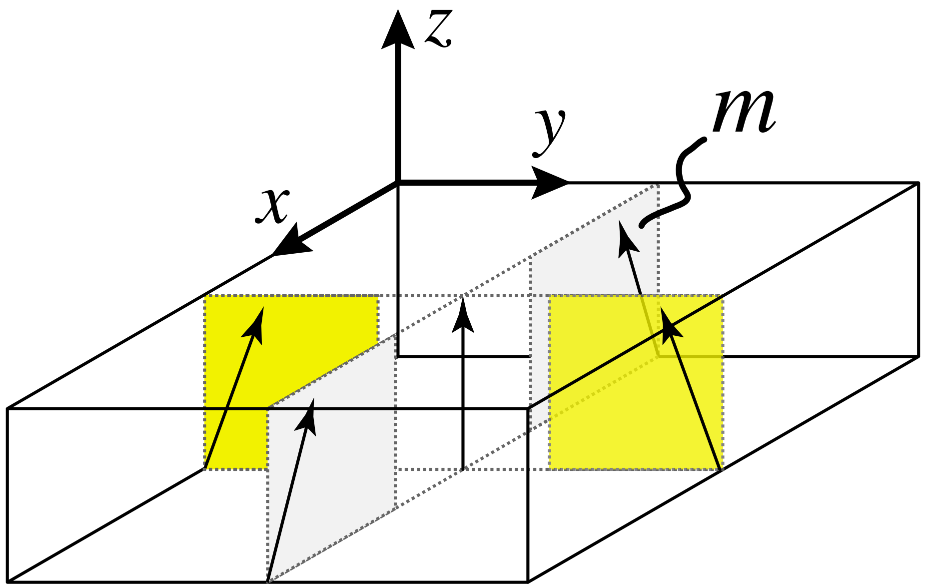
Magnetization tilts at edges

- In nominally uniformly-magnetized systems, magnetization tilts still occur at <u>edges</u> due to DMI

- In continuum approximation, variational procedure leads to nontrivial boundary conditions

$$\boxed{\frac{\partial U'}{\partial \vec{m}}} + \frac{\partial \vec{U}}{\partial(\nabla \vec{m})} \cdot \vec{n} = 0 \quad \Rightarrow \quad 2A\frac{\partial m_y}{\partial y} = -Dm_z \quad etc.$$

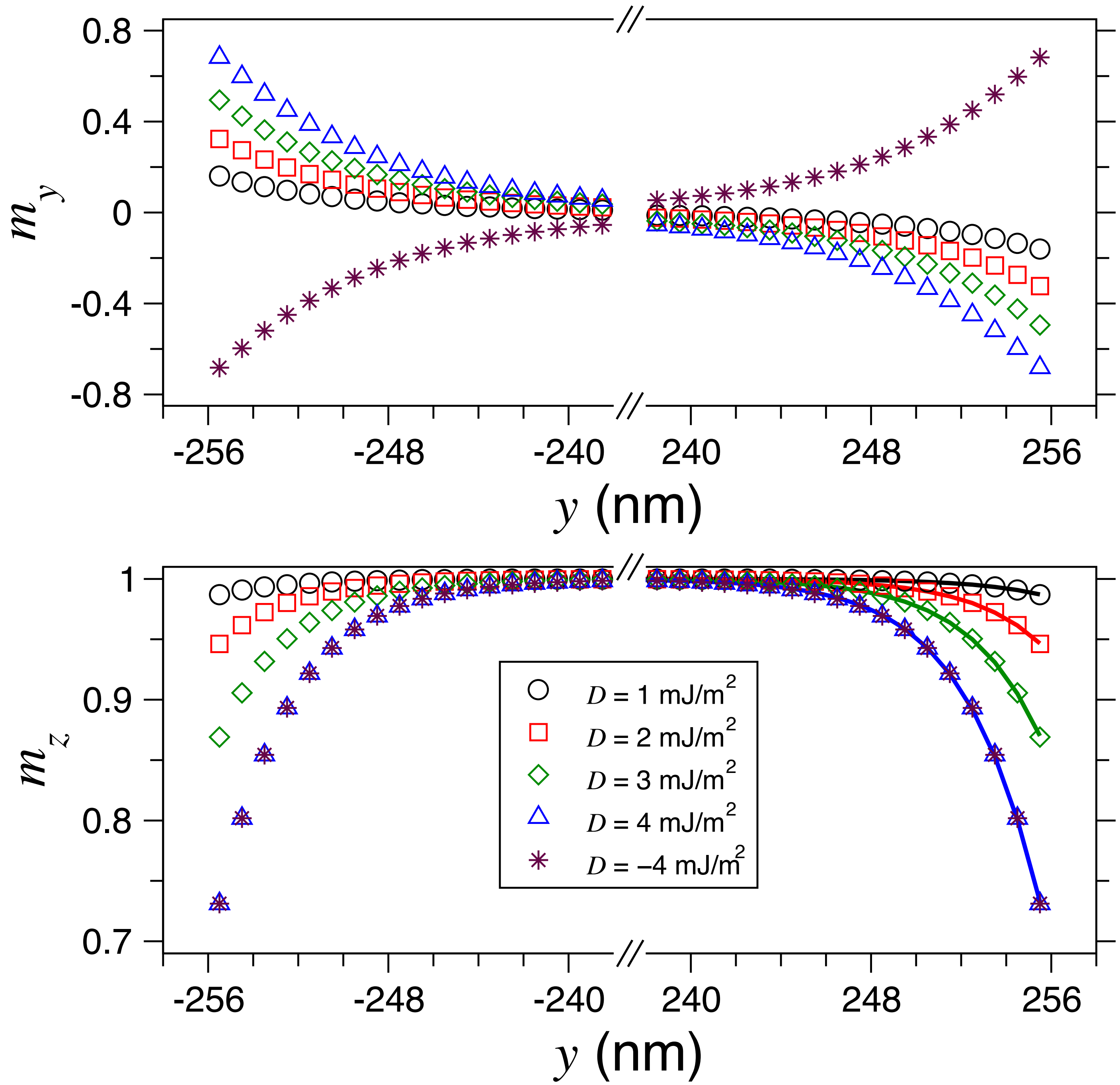
surface anisotropies, etc.



F. Garcia-Sanchez, JVK, *et al.*, Phys. Rev. B **89**, 224408 (2014)

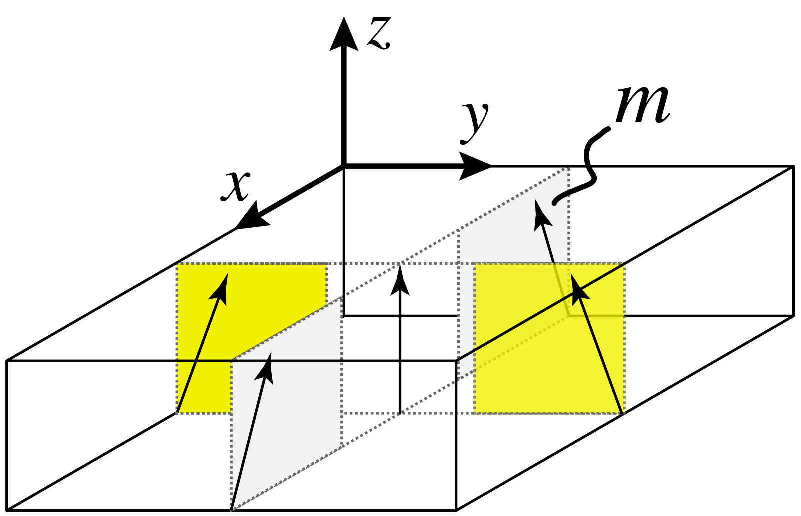
Magnetization tilts at edges

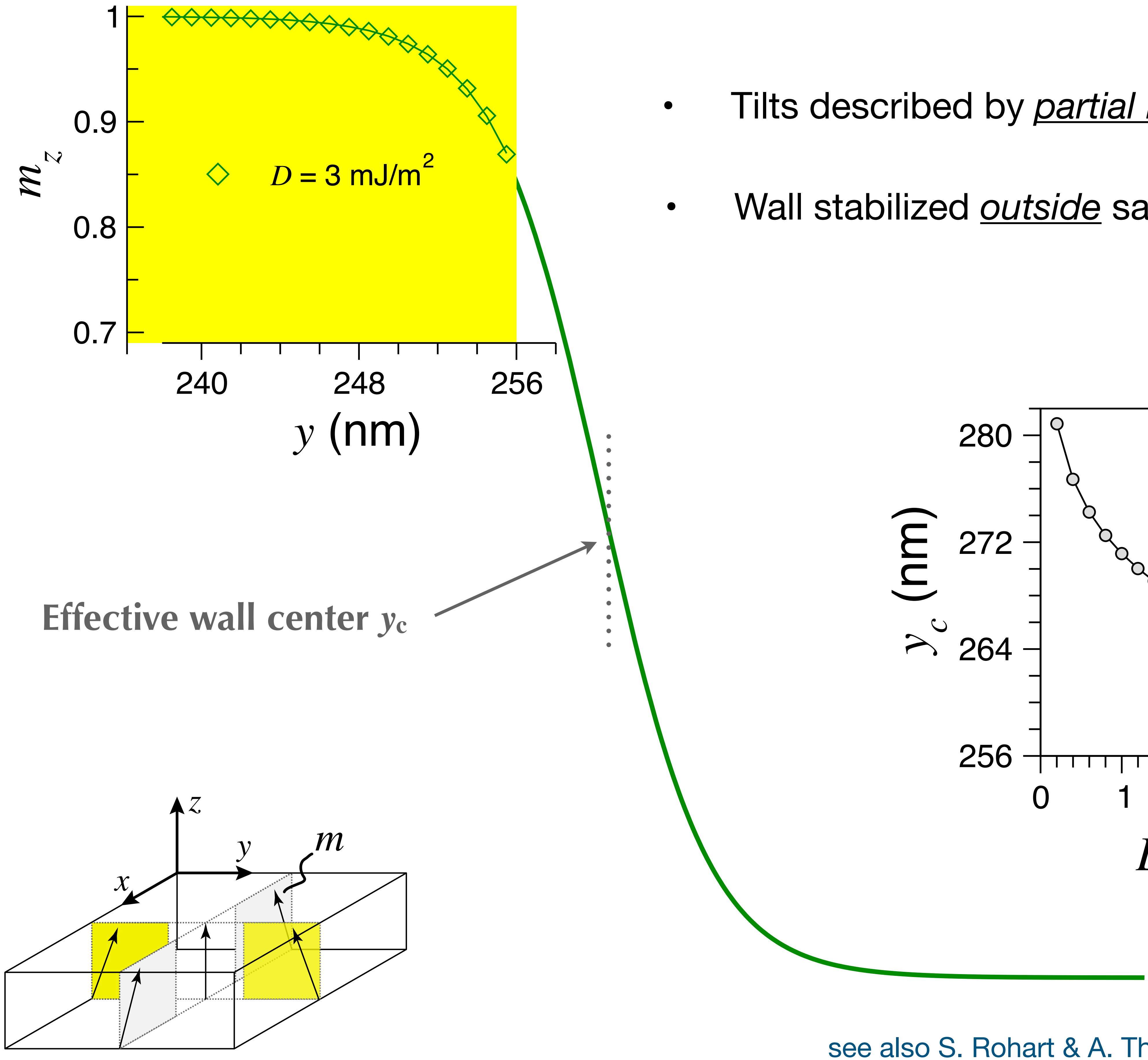
F. Garcia-Sanchez, JVK, *et al.*, Phys. Rev. B **89**, 224408 (2014)



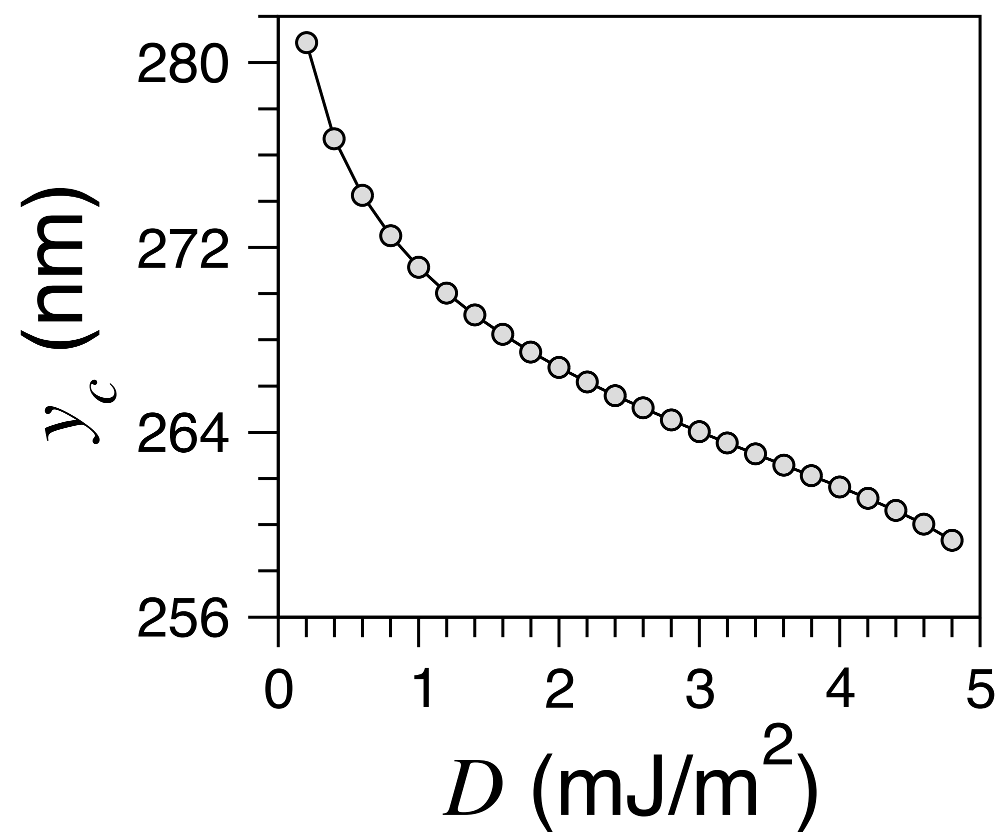
Boundary conditions:

$$2A\frac{\partial m_y}{\partial y} = -Dm_z \qquad etc.$$





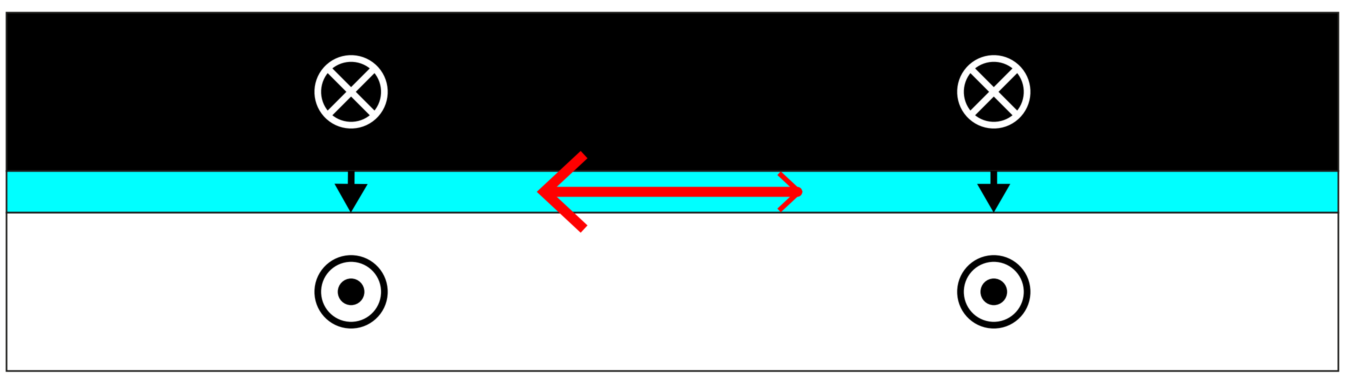
- Tilts described by ***partial Néel walls***
- Wall stabilized ***outside*** sample by DMI



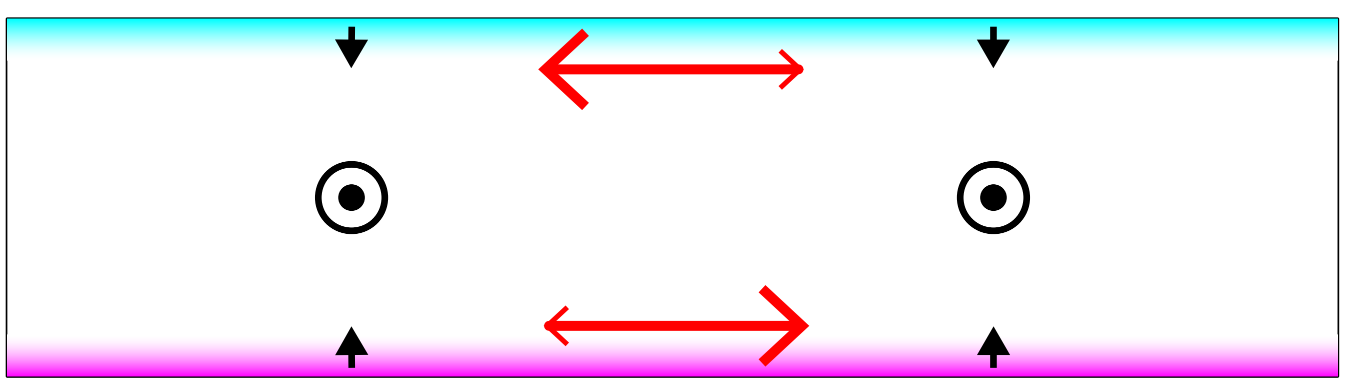
see also S. Rohart & A. Thiaville, Phys. Rev. B (2013)

Channeling along edge tilts

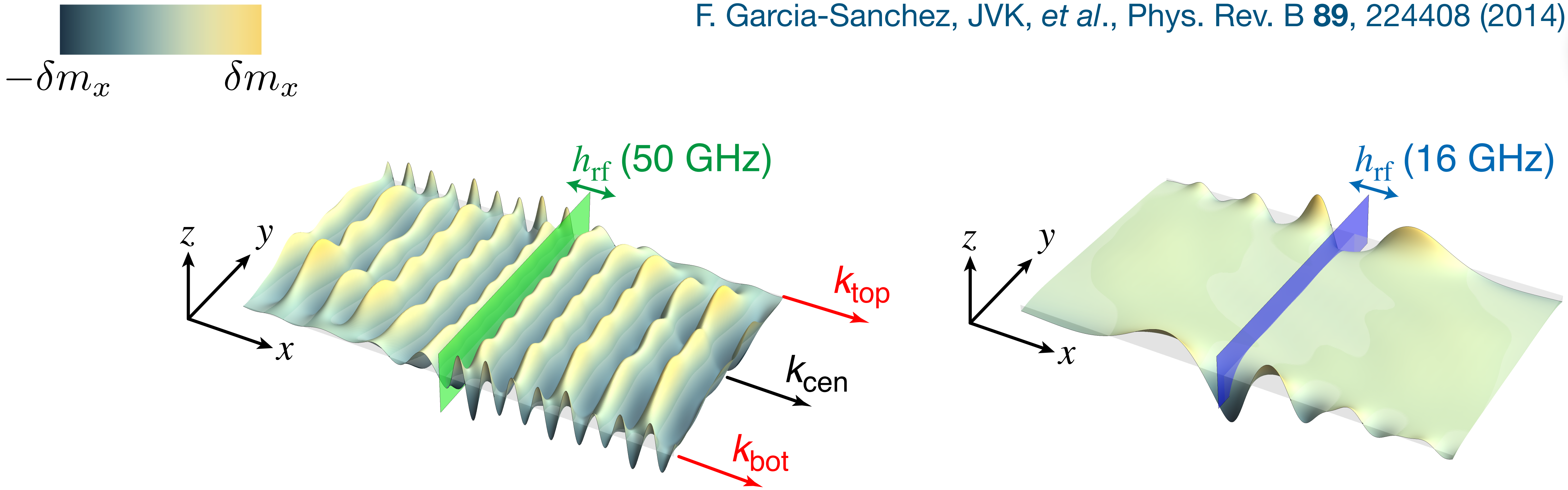
- Partial Néel walls at edges should lead to similar nonreciprocal propagation as seen in full Néel domain walls

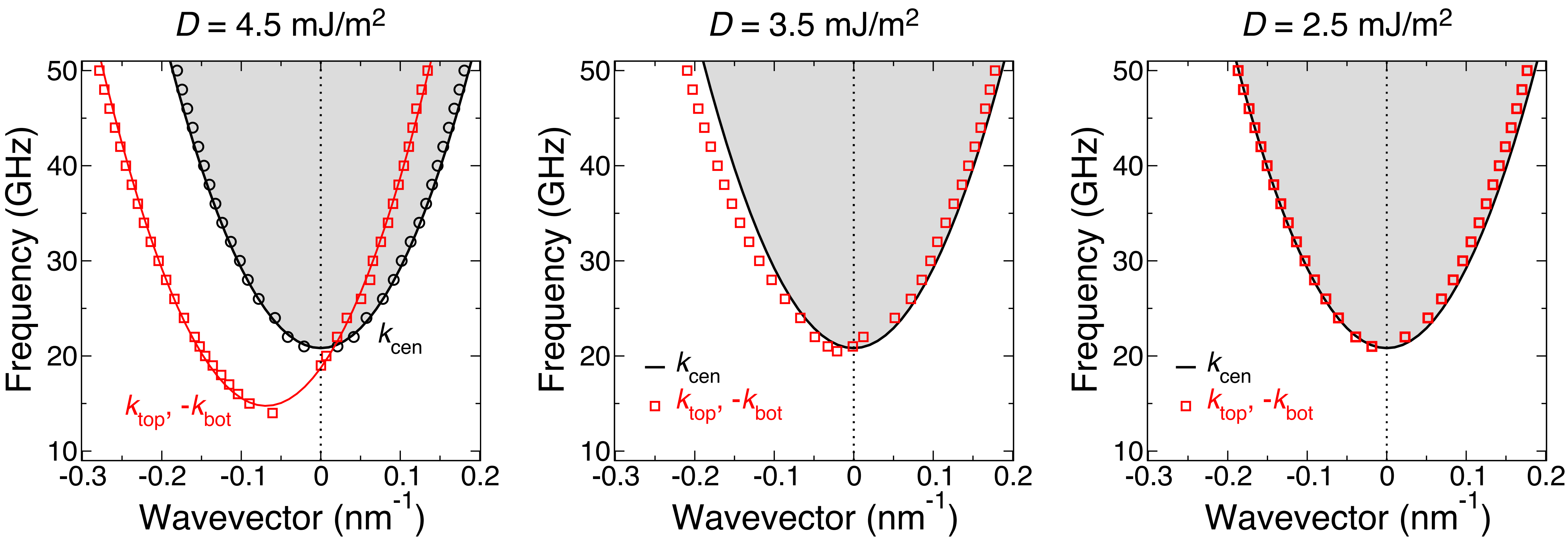


Nonreciprocal channelling along wall

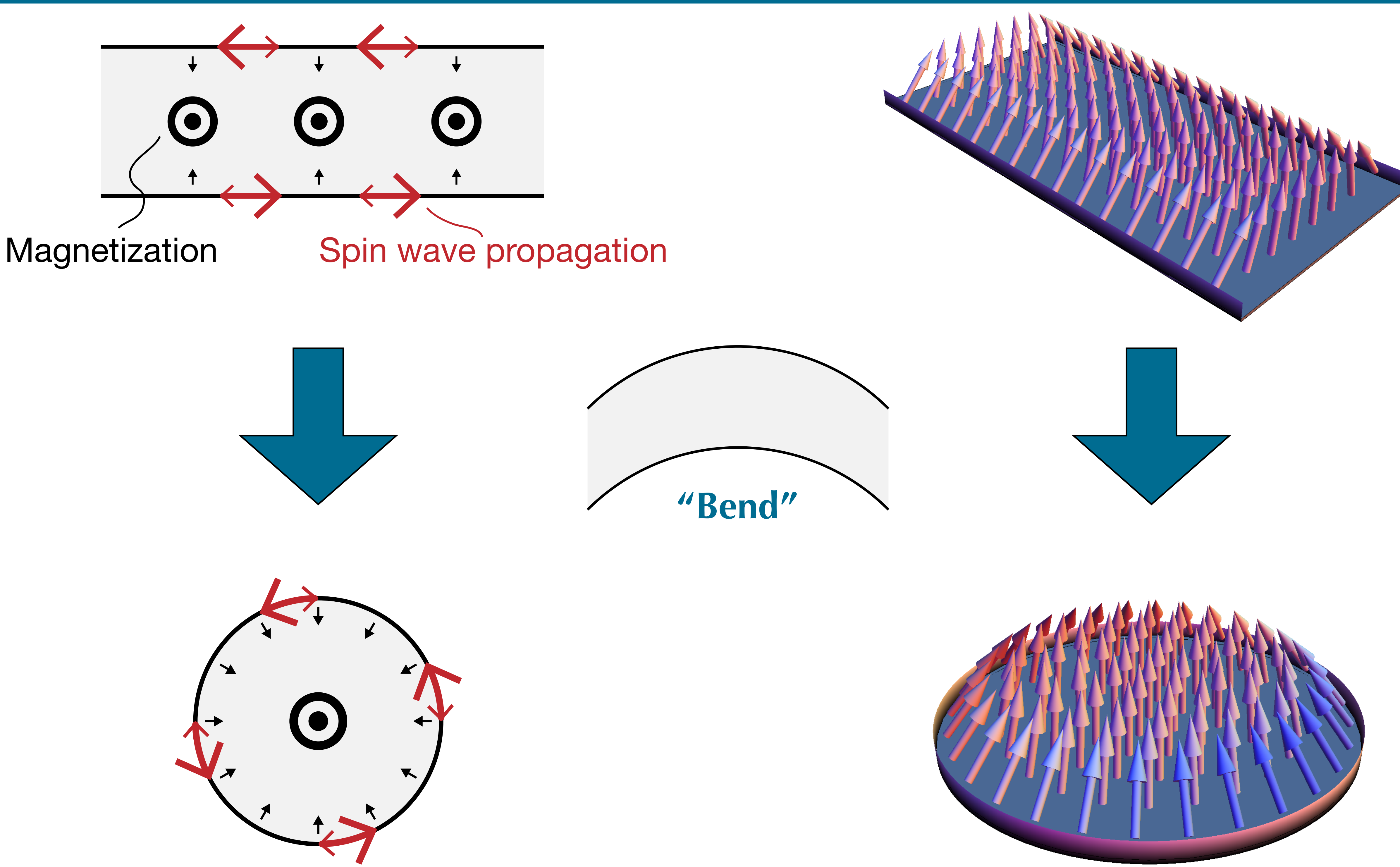


Different channelling directions at top and bottom edges?

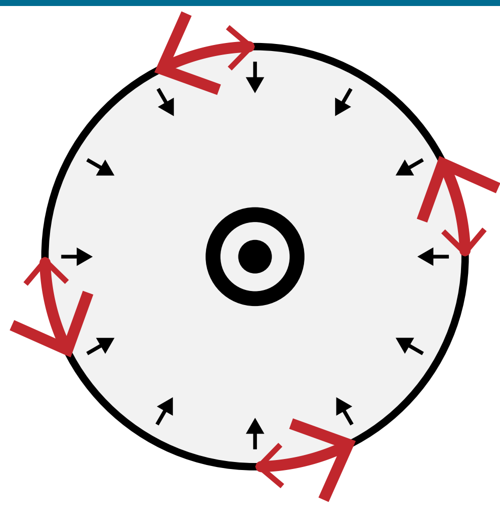

$-\delta m_x$
δm_x
h_{rf} (50 GHz)
k_{top}
k_{cen}
k_{bot}
z
y
x
h_{rf} (16 GHz)


D = 4.5 mJ/m^2
D = 3.5 mJ/m^2
D = 2.5 mJ/m^2
Frequency (GHz)
Wavevector (nm^{-1})
k_{cen}
k_{top}, $-k_{bot}$

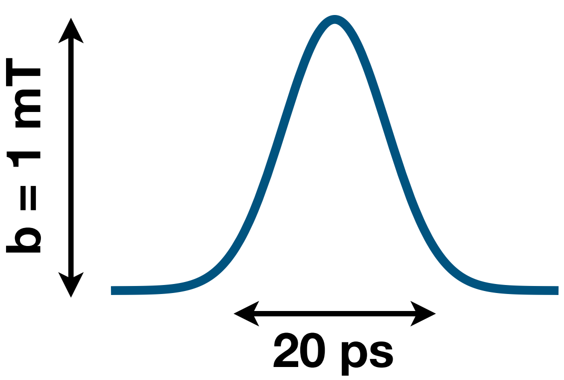
Confined geometries: Dots



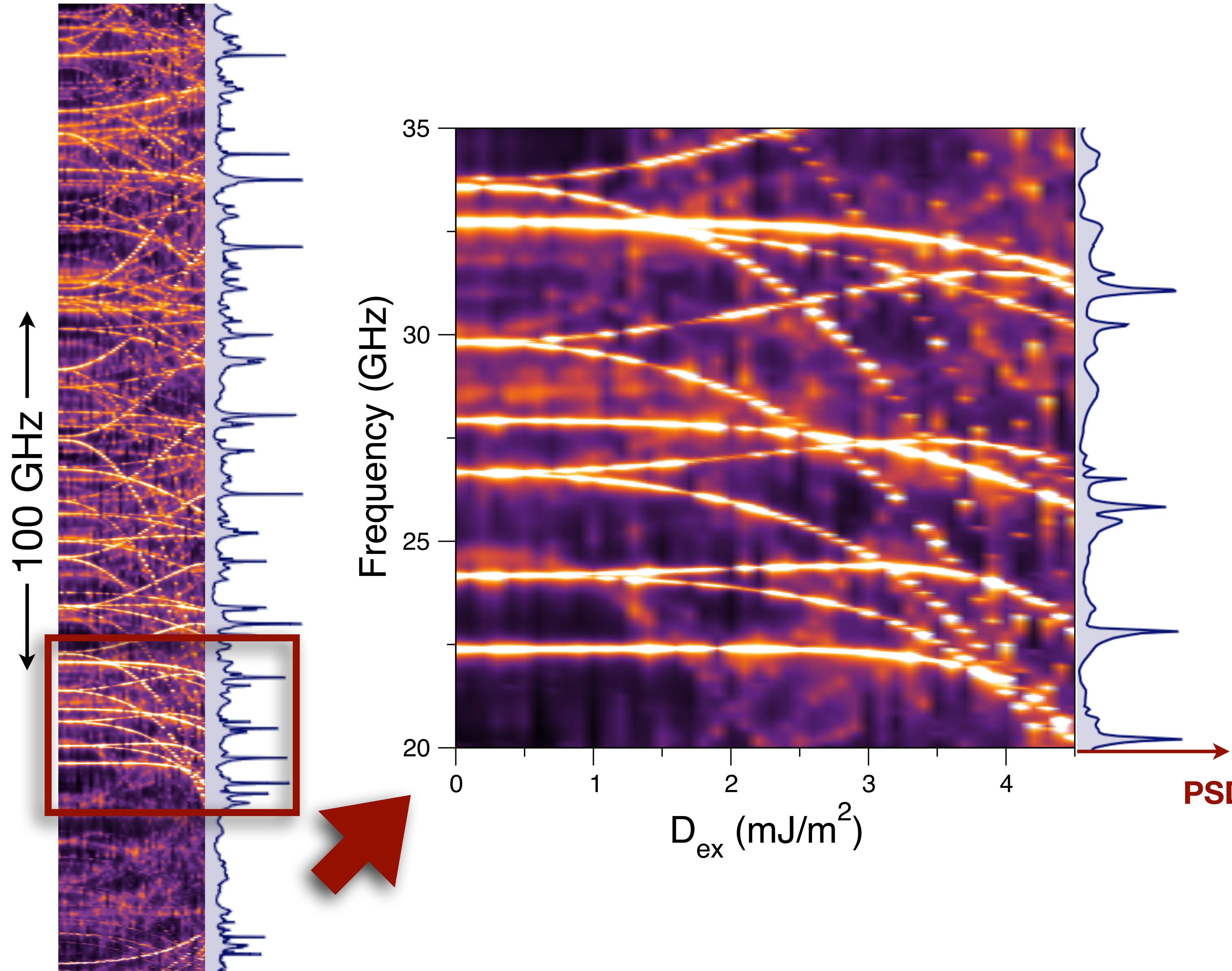
Eigenmode spectrum from transient response



d =100 nm

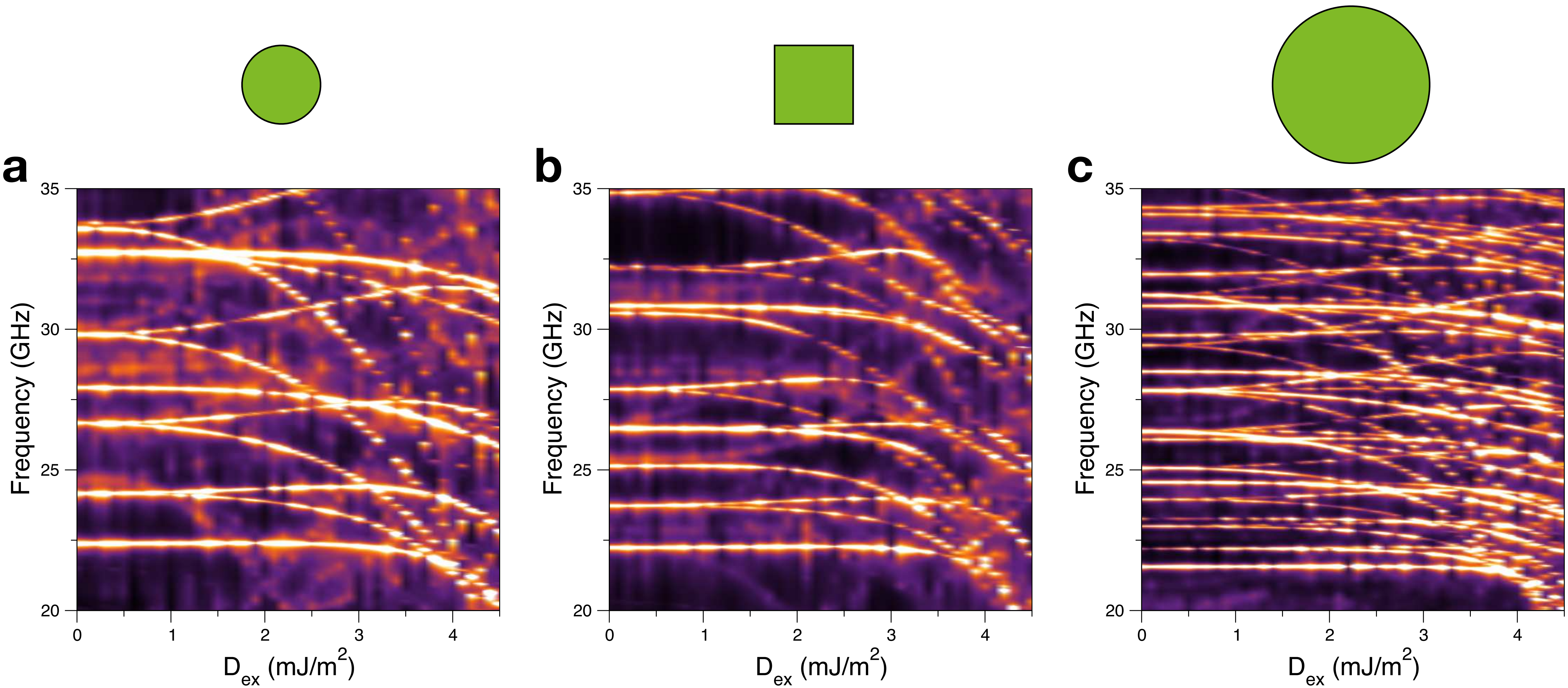


Field pulse

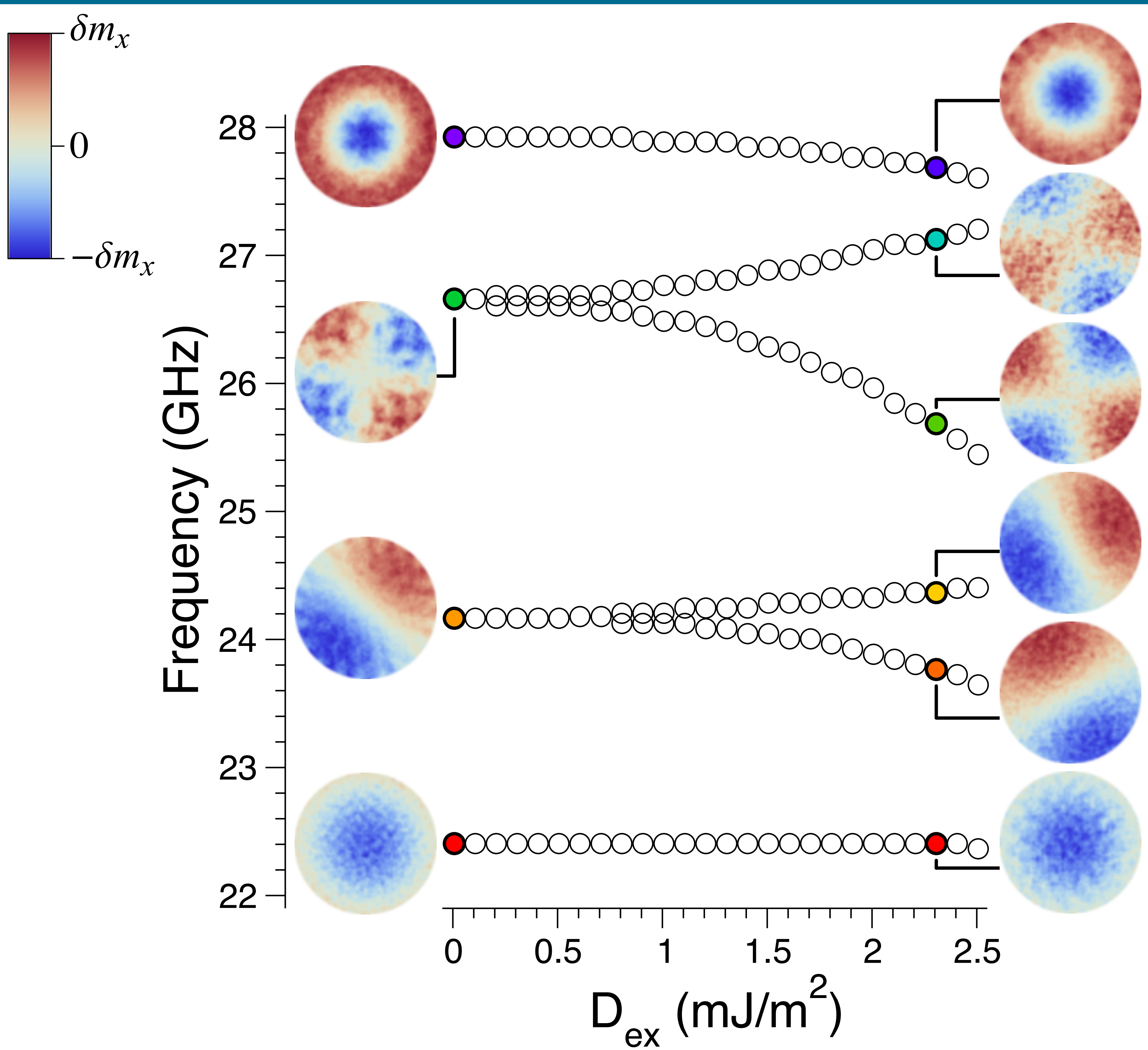


Splitting of mode frequencies as strength of DMI increases

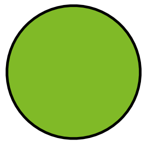
100 nm diameter | **100 nm wide** | **200 nm diameter**



Mode splitting in circular dots

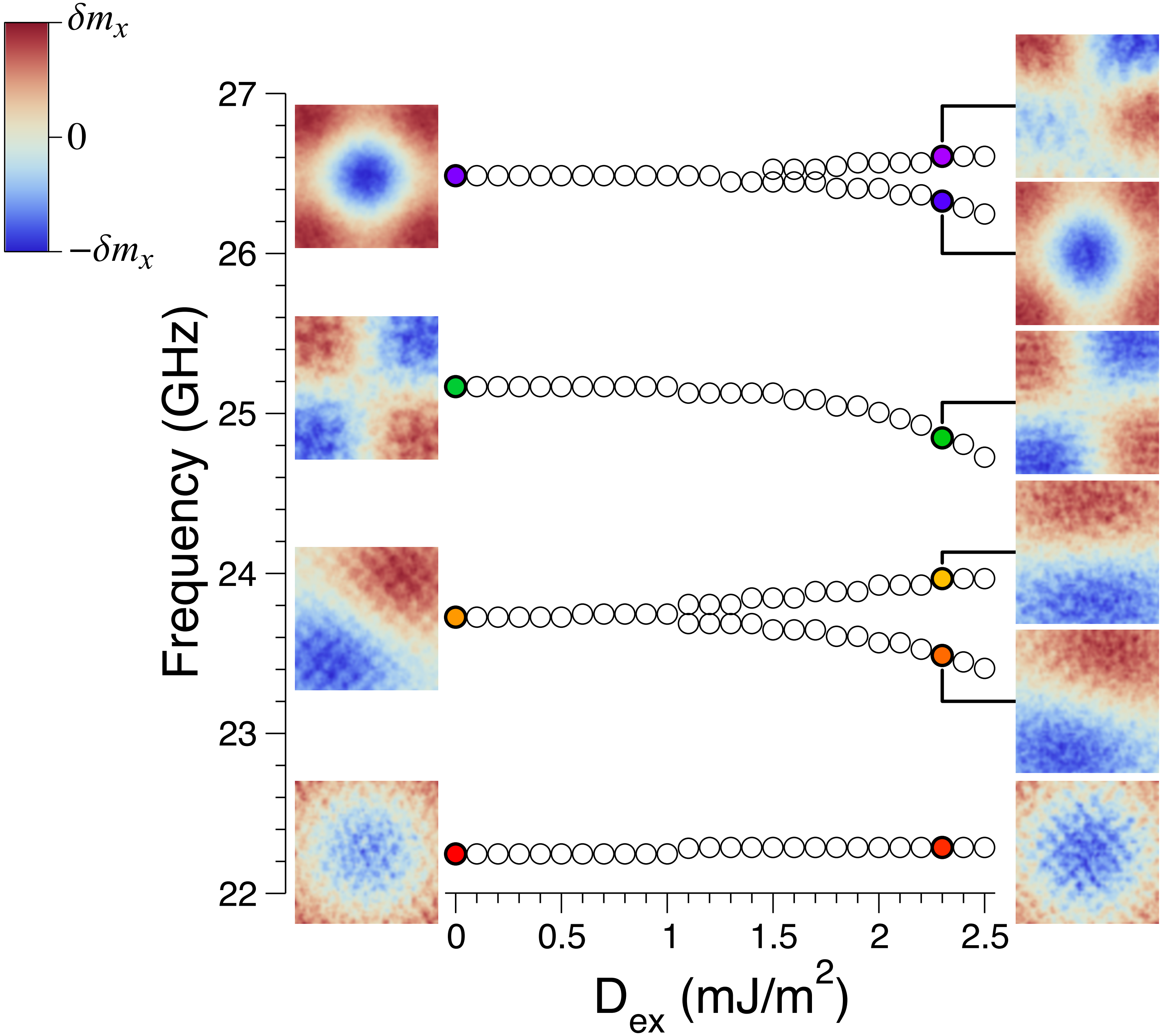


100 nm diameter

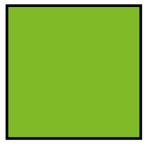


- Azimuthal modes are more strongly affected by tilts at edges
- DMI lifts degeneracy between CW and CCW azimuthal modes

Mode splitting in square dots



100 nm wide



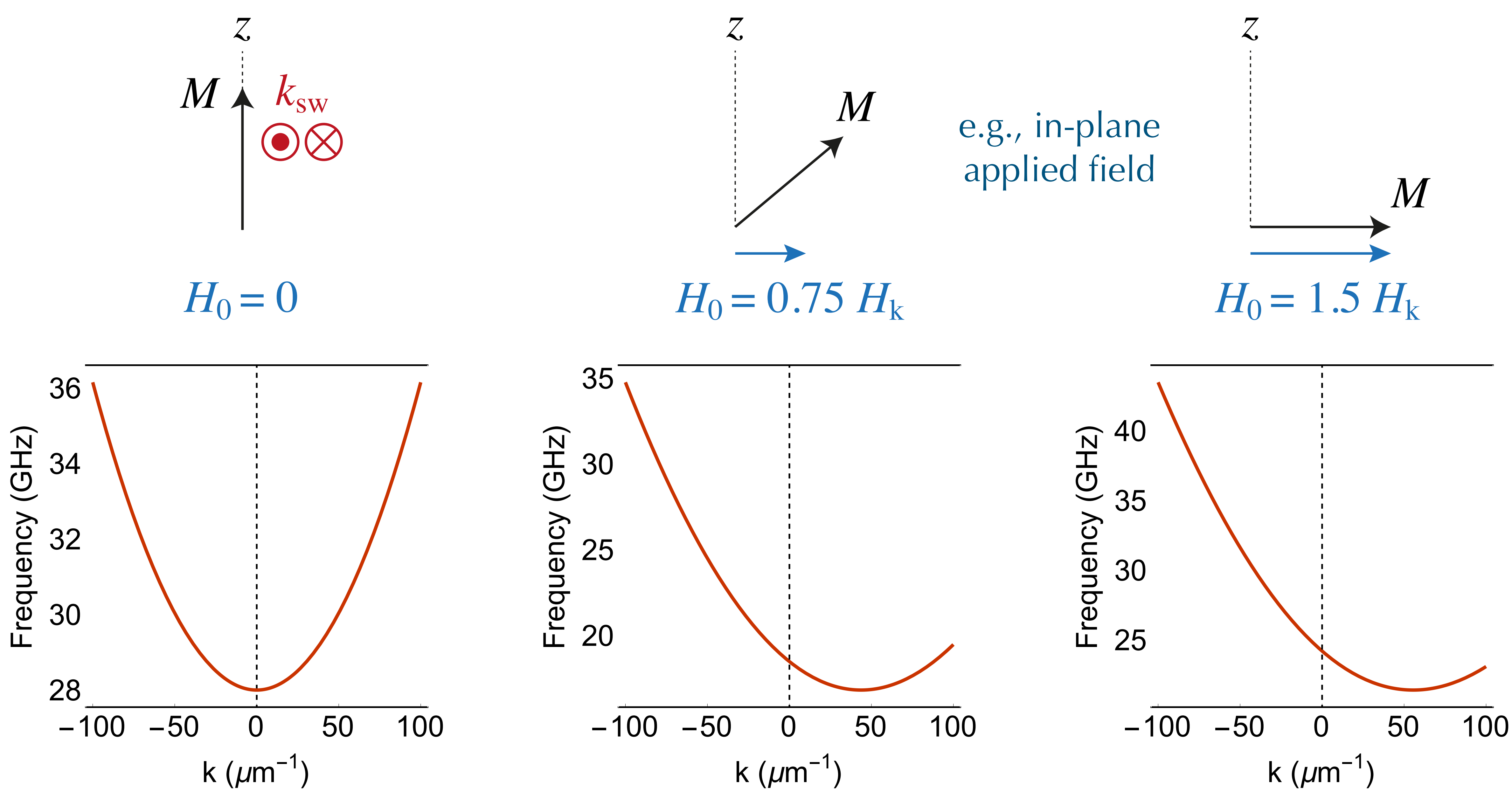
Similar mode splitting observed in square dots

Talk outline

- Part 1: Brief overview of chiral interactions and spin waves
- Part 2: Spin wave channelling in chiral walls
  - *Nonreciprocal propagation along Néel walls*
  - *Curved magnonic waveguides*
- Part 3: Edge modes in nanostructures
  - *Tilted spin states at dot edges*
- Part 4: Brillouin light spectroscopy measurements
  - *Pt/Co/AlOx, [W, Hf]/CoFeB/MgO*

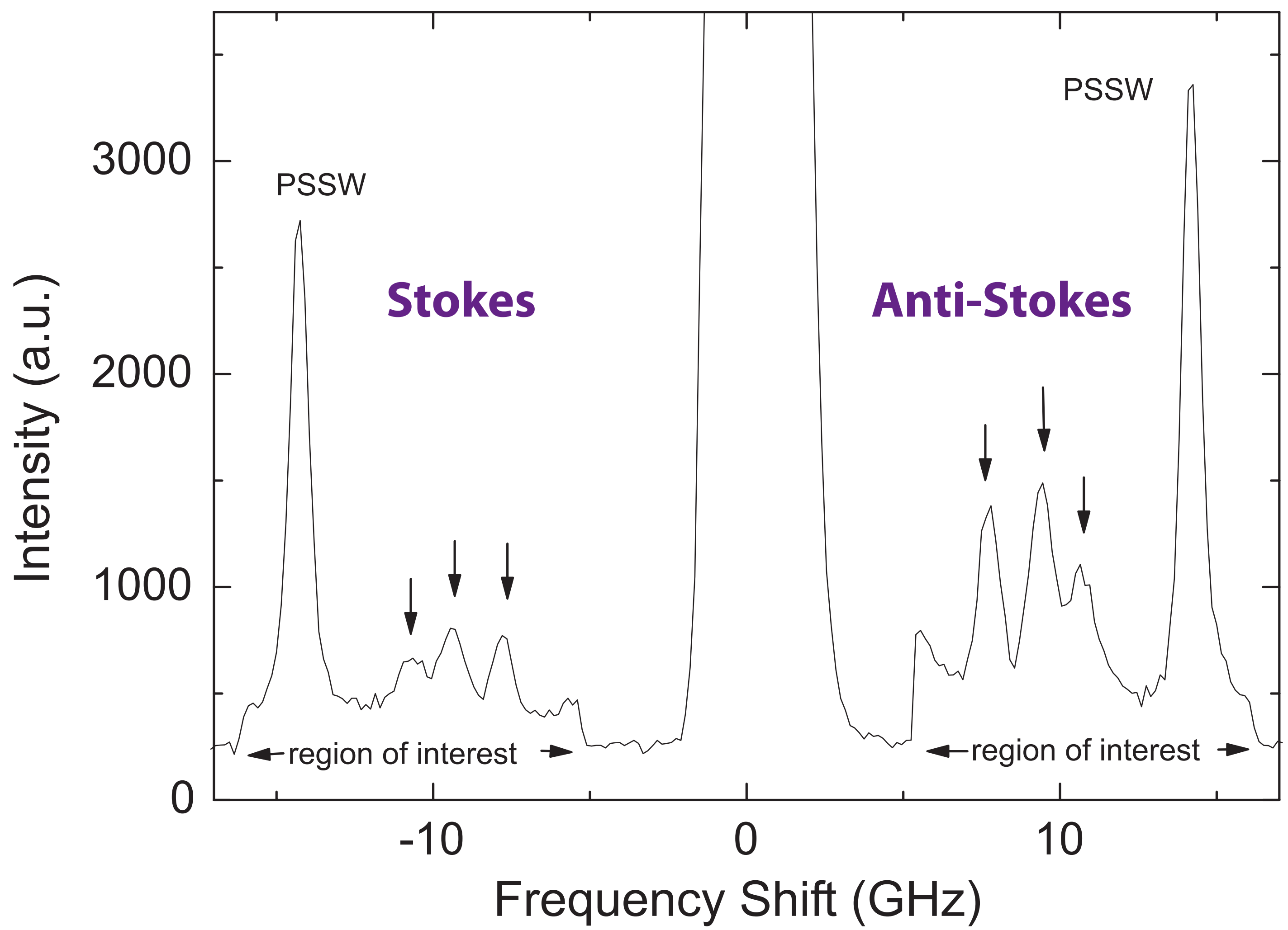
Nonreciprocity with magnetization tilts

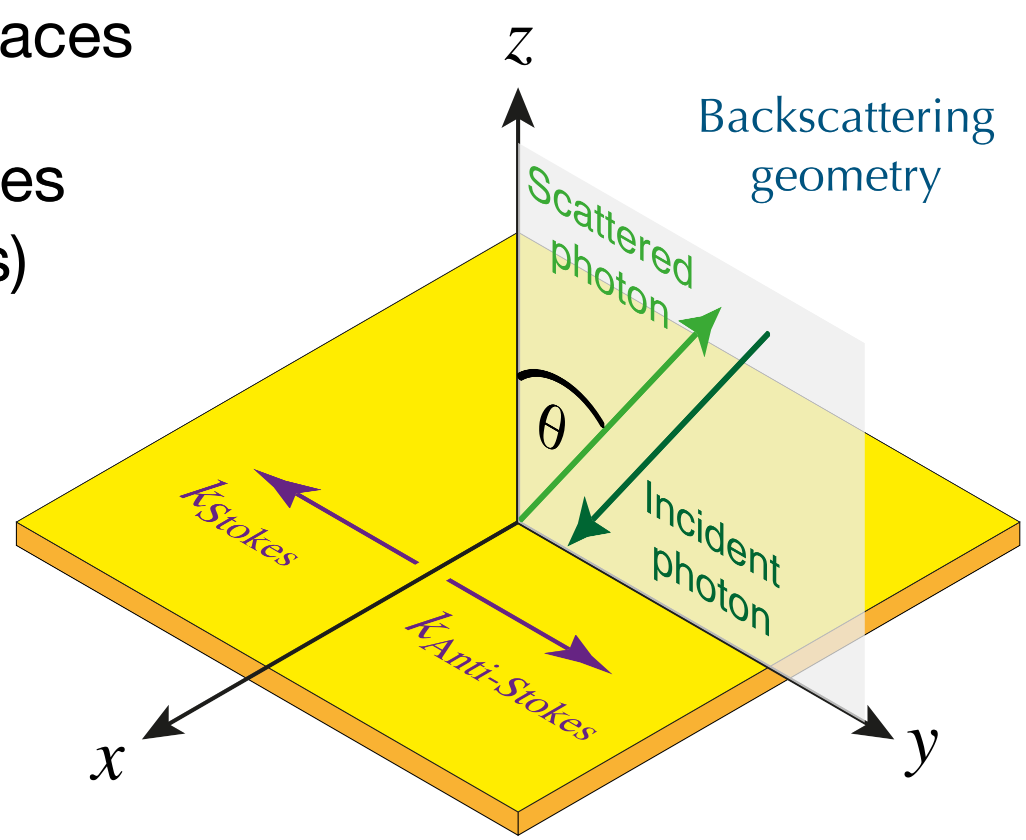
- In uniformly-magnetized films, DMI can lead to nonreciprocal spin wave propagation with symmetry-breaking fields

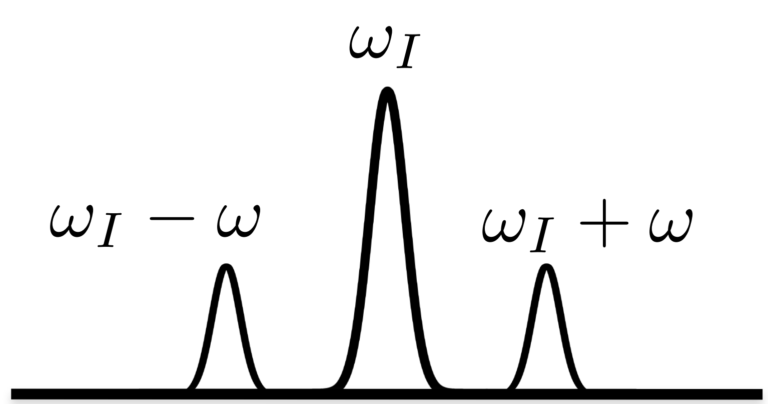


Brillouin light spectroscopy of spin waves

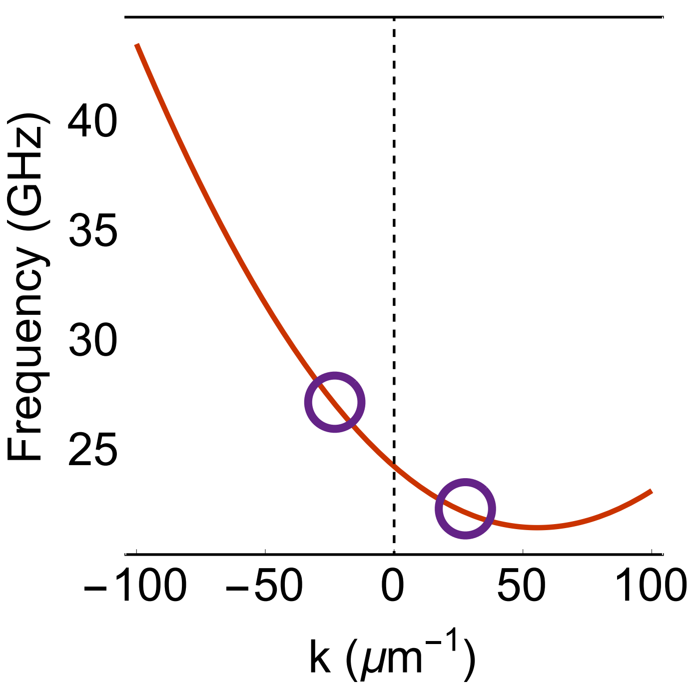
- Probe spin wave spectra by scattering light off surfaces
- Reflected photons give information about spin waves that are created (Stokes) or annihilated (anti-Stokes)

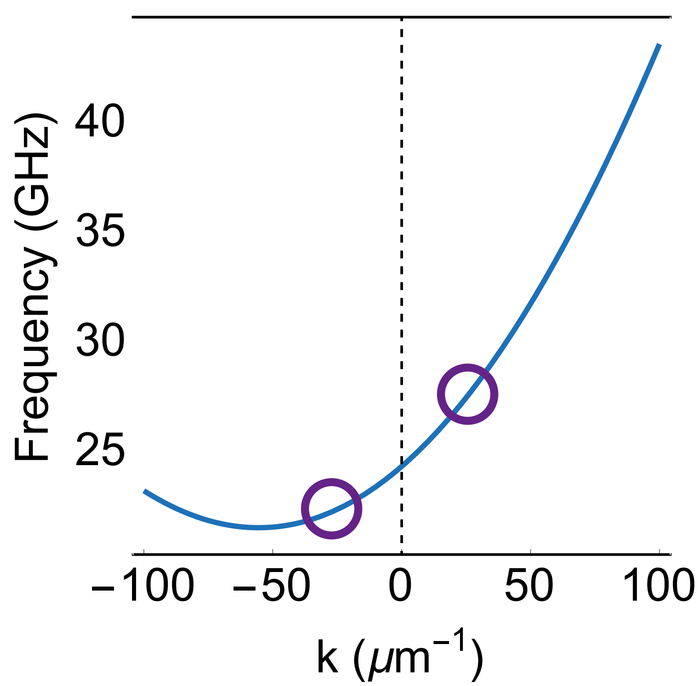


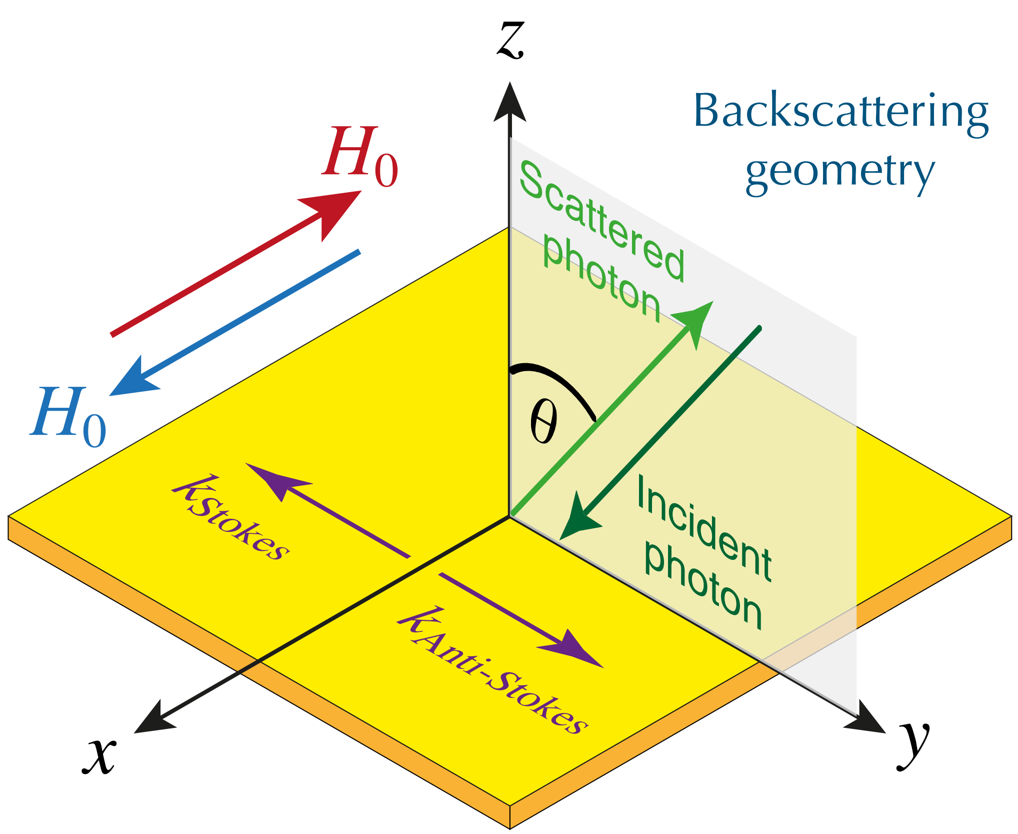


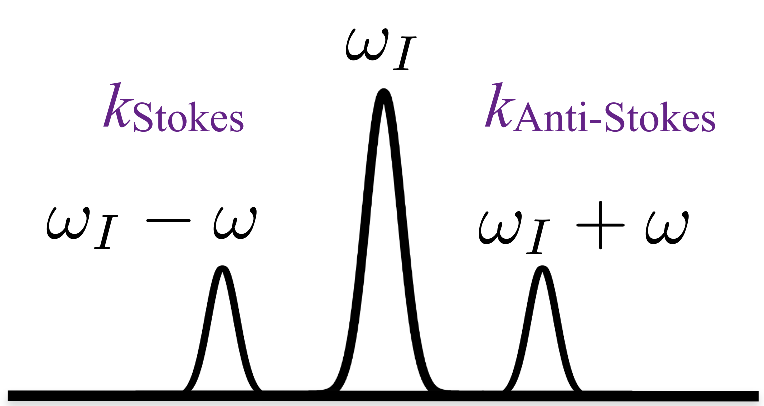


Brillouin light spectroscopy of spin waves



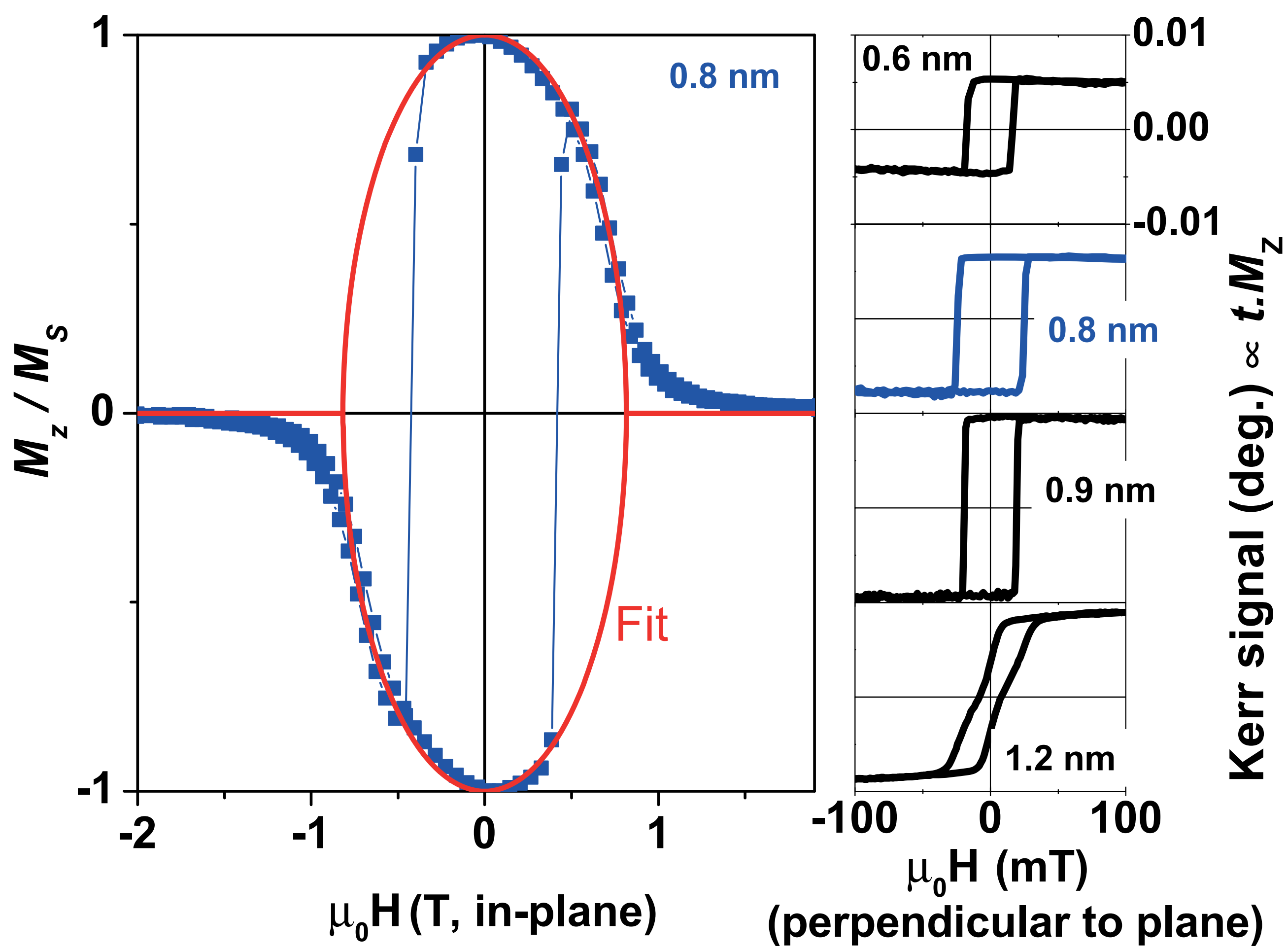


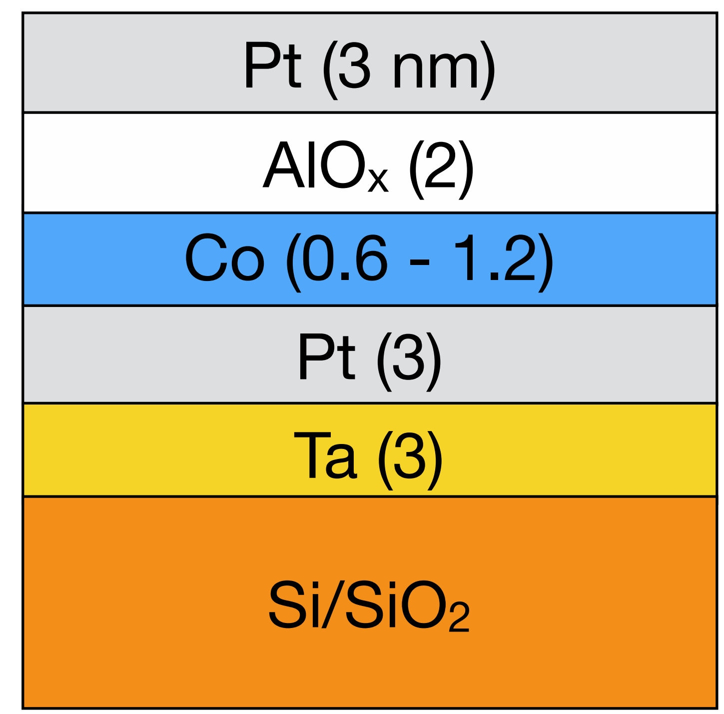




Experiments on Pt/Co/AlOx

- Sputtered perpendicularly-magnetized Pt/Co/AlOx films, variable Co film thickness

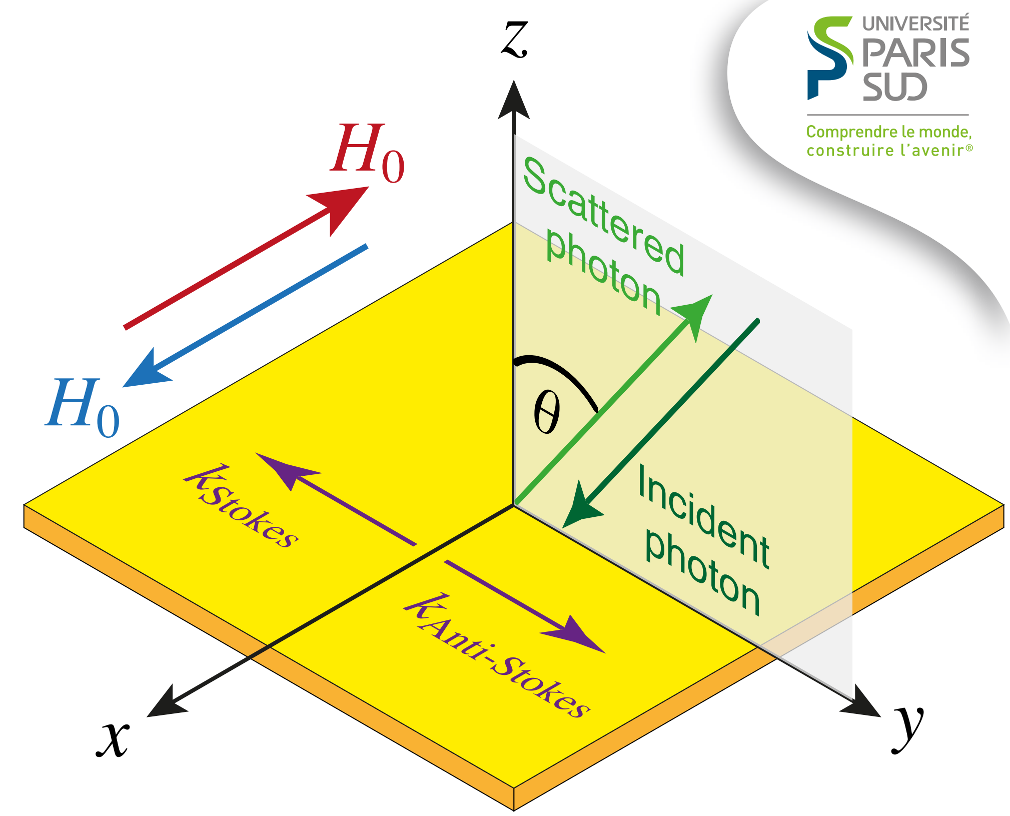


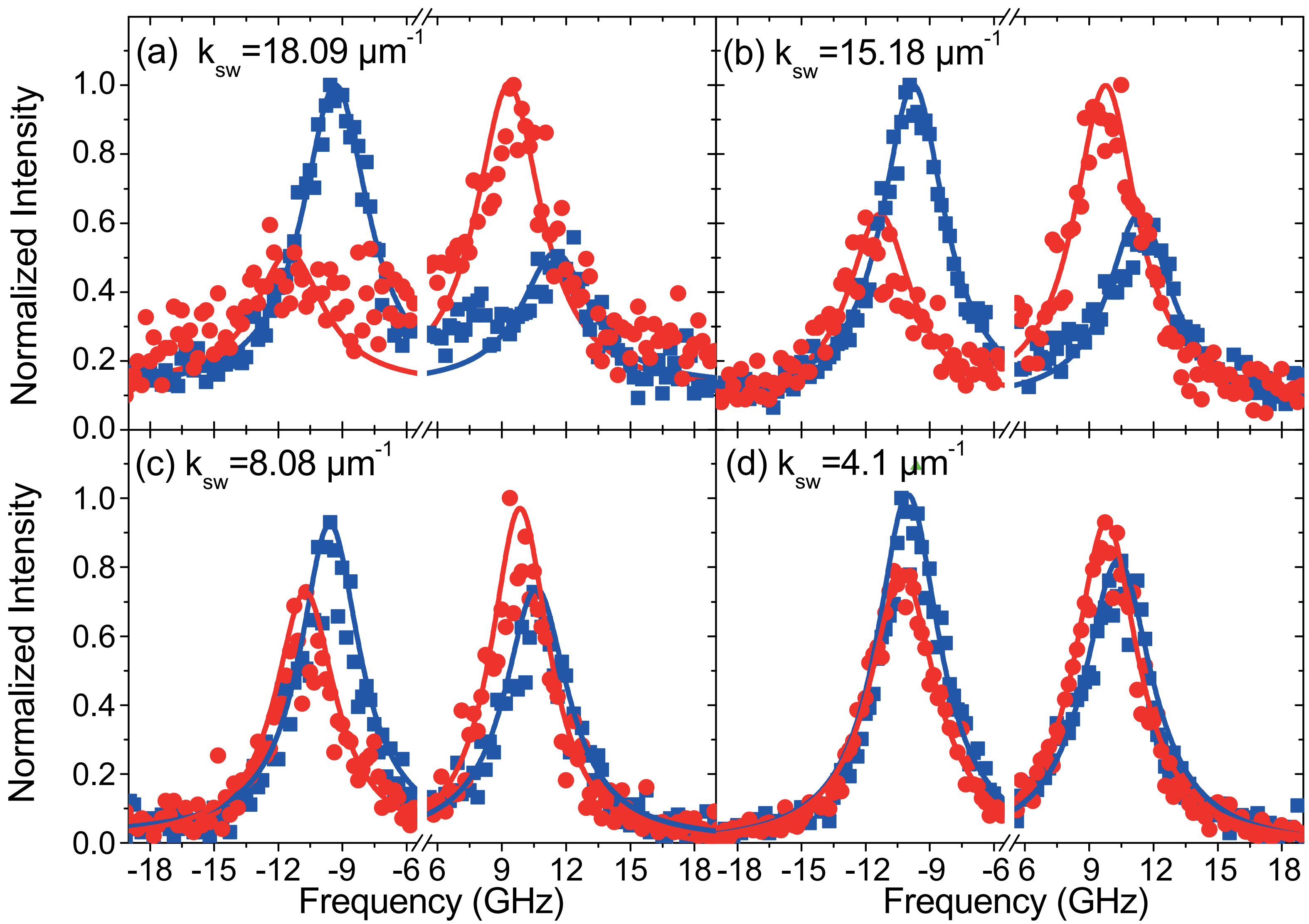


M. Belmeguenai, ..., JVK *et al*., Phys. Rev. B **91**, 180405(R) (2015)

- Nonreciprocal propagation observed, as expected for finite DMI

see also
K. Zakeri *et al.*, Phys. Rev. Lett. **104**, 137203 (2010)
J.-H. Moon *et al.*, Phys. Rev. B **88**, 184404 (2013)
K. Di *et al.*, Phys. Rev. Lett. **117**, 047201 (2015)
K. Di *et al.*, Appl. Phys. Lett. **106**, 052403 (2015)





$$k_{\mathrm{sw}} = 4\pi \sin(\theta)/\lambda$$
$$\lambda = 532 \text{ nm}$$

$\mu_0 H_0 = \pm\, 0.4$ T

Pt / Co (1.2 nm) / AlO_x

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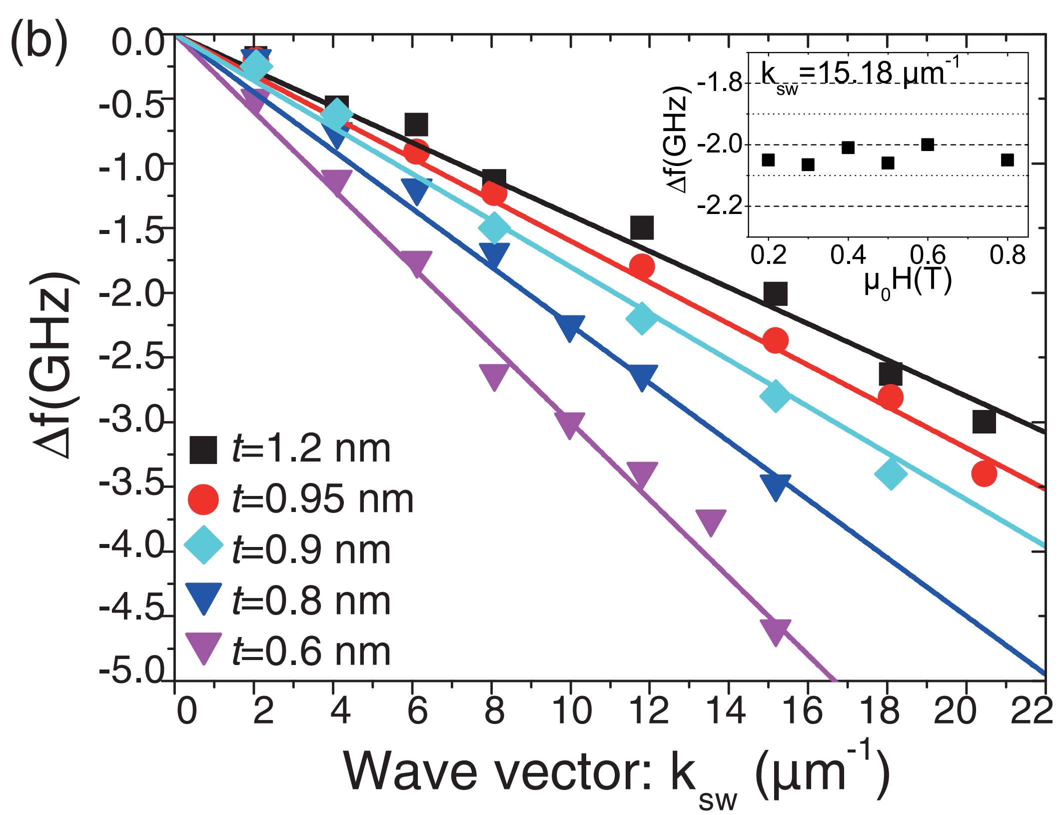
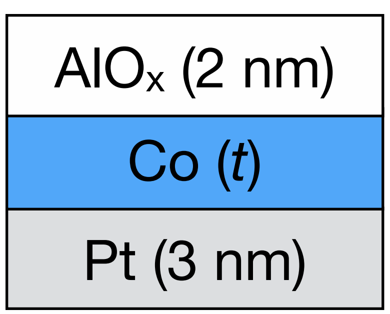
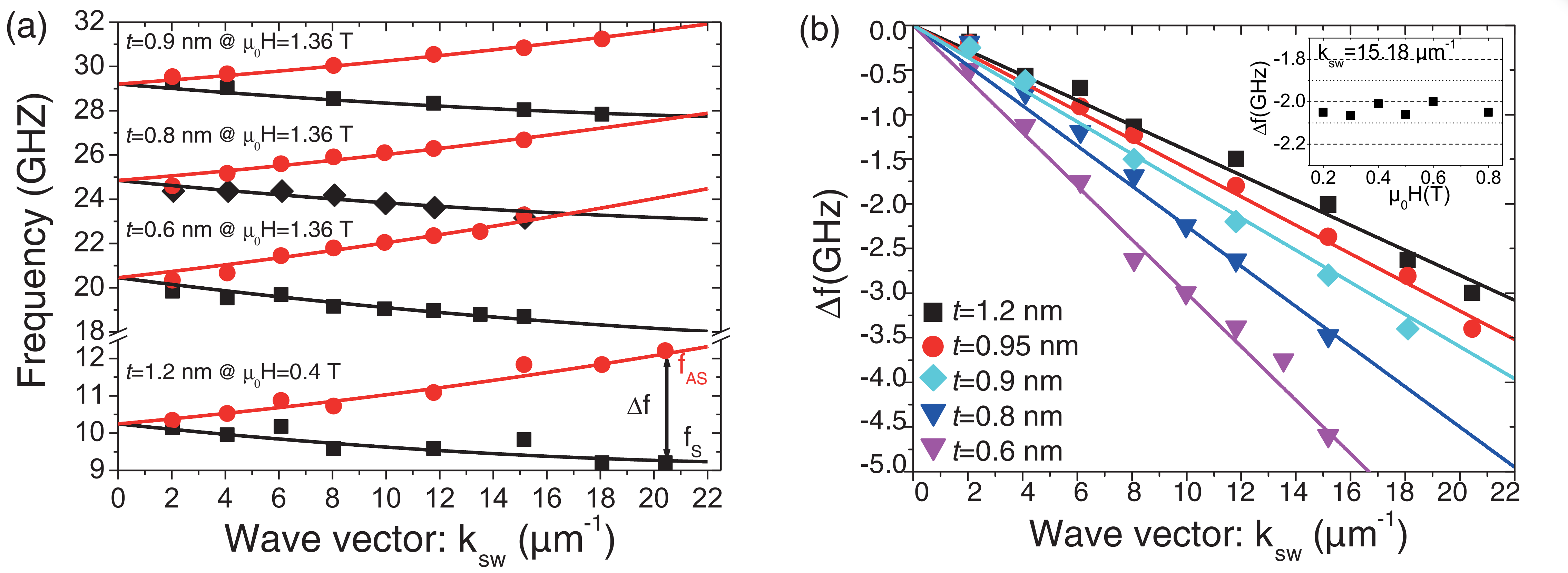


$$\Delta f = f_S - f_{AS} = \frac{2\gamma}{\pi M_s} D k_{sw} = \frac{2\gamma}{\pi M_s}\frac{D_s}{t} k_{sw}$$

Consistent with single interface value of
***D*$_s$ = –1.7 pJ/m** (*left-handed chirality*)



t (nm)	$\mu_0 M_s$ (T)	$\mu_0 H_{sat}$ MOKE (T)	$\mu_0 H_{K_{eff}}$ BLS (T)	$-D_{eff}$ (mJ/m^2)	$-D_s$ (pJ/m)
0.6	1.38	0.95	1.03	2.71 ± 0.16	1.63 ± 0.1
0.8	1.48	0.82	0.87	2.18 ± 0.25	1.75 ± 0.2
0.9	1.51	0.75	0.68	1.88 ± 0.08	1.69 ± 0.07
0.95	1.68	0.51	0.36	1.76 ± 0.24	1.67 ± 0.23
1.2	1.71	0.10	0.11	1.57 ± 0.18	1.88 ± 0.22



$$f = \frac{\gamma_0}{2\pi}\sqrt{\left(H_0 + \frac{2A}{\mu_0 M_s}k_{\mathrm{sw}}^2\right)\left(H_0 - H_k + \frac{2A}{\mu_0 M_s}k_{\mathrm{sw}}^2\right)} \boxed{- \frac{\gamma D}{\pi M_s}k_{\mathrm{sw}}}$$

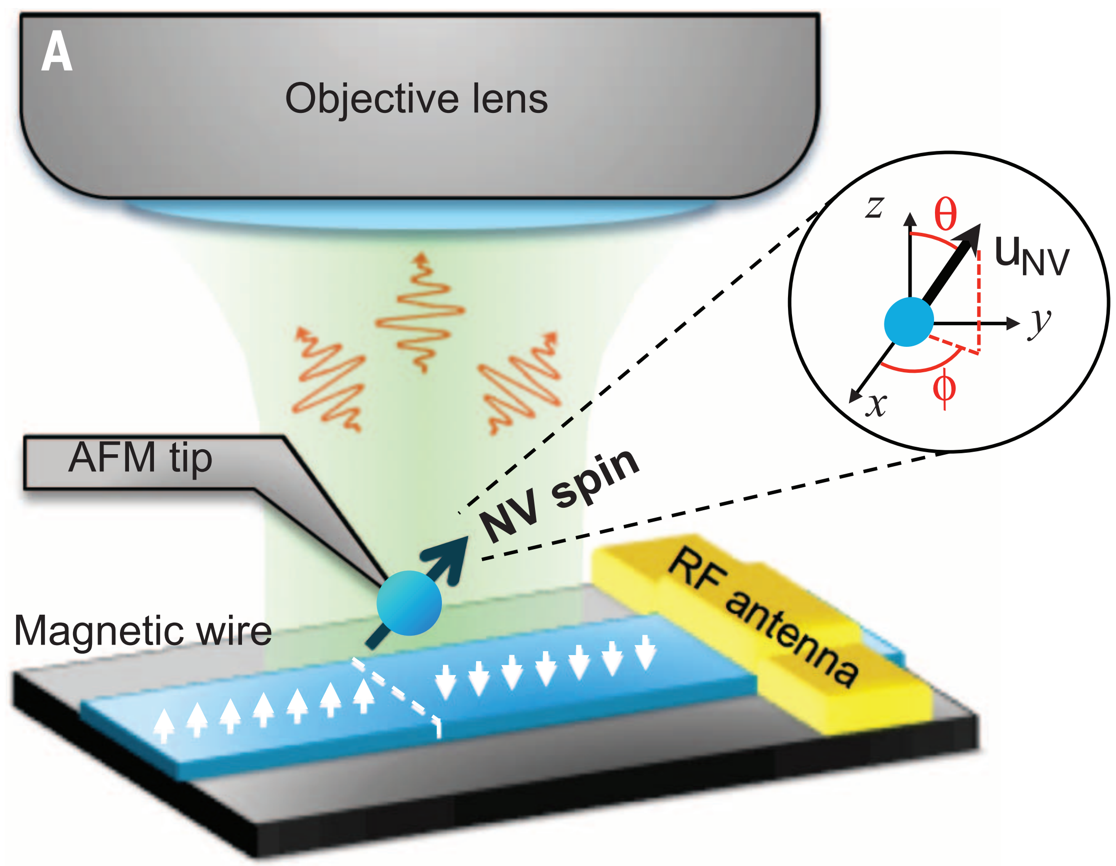
Nonreciprocity due to DMI

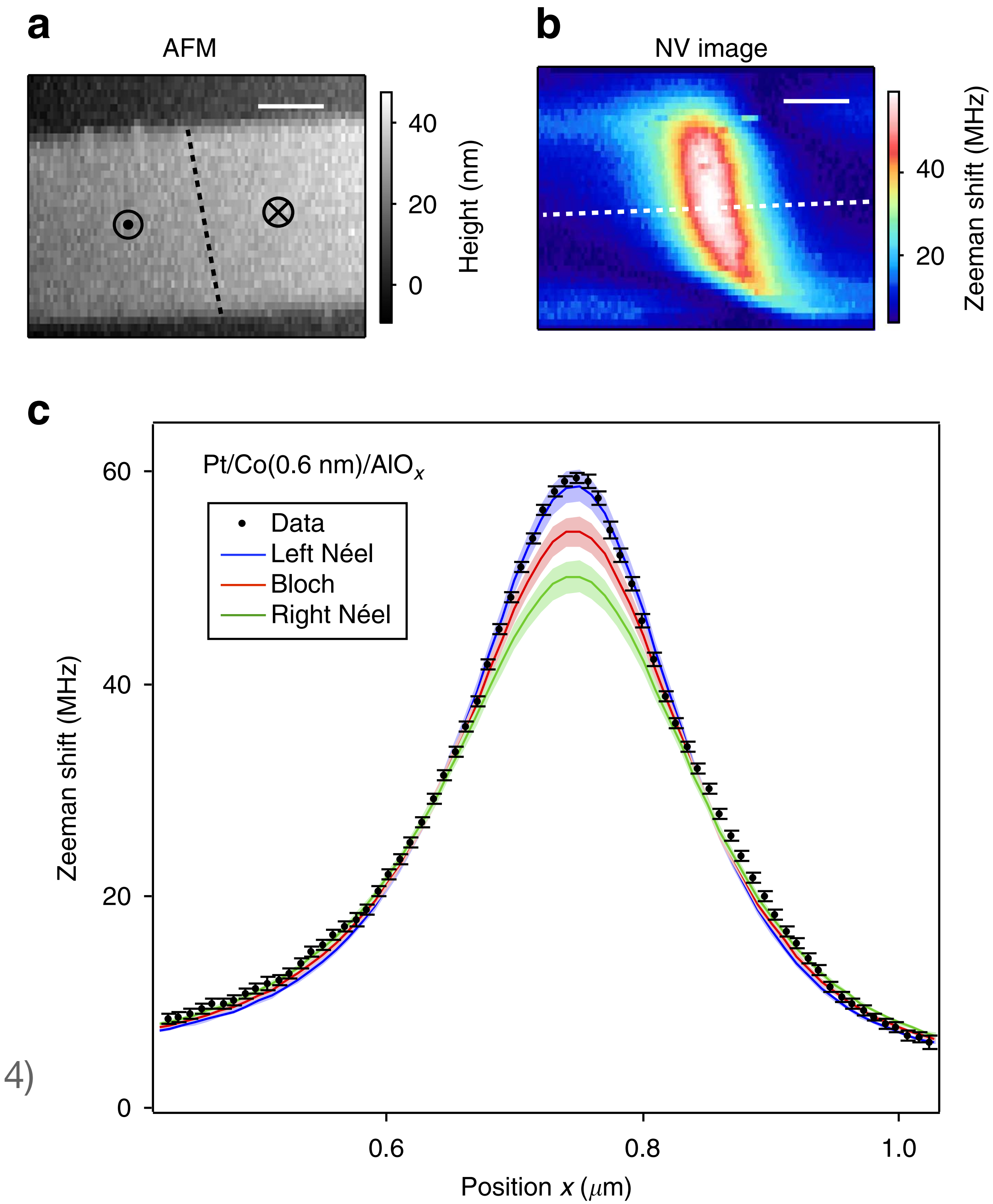
$$\Delta f = f_{\mathrm{S}} - f_{\mathrm{AS}} = \boxed{\frac{2\gamma}{\pi M_s}} D k_{\mathrm{sw}} = \boxed{\frac{2\gamma}{\pi M_s}\frac{D_s}{t}} k_{\mathrm{sw}}$$

Slope gives measure of DMI constant

M. Belmeguenai, ..., JVK *et al.*, Phys. Rev. B **91**, 180405(R) (2015)

- Left-handed chiral Néel walls observed in Pt/Co/AlOx films using nitrogen-vacancy center magnetometry





L. Rondin *et al*., Rep. Prog. Phys. **77**, 056503 (2014)
J.-P. Tétienne, T. Hingant, JVK, *et al*., Science **344**, 1366 (2014)
J.-P. Tétienne, ..., JVK *et al*., Nat. Commun. **6**, 6733 (2015)

Summary

- Nonreciprocal spin wave channelling along Néel walls, edges

- DMI lifts degeneracy of azimuthal modes in dots

- DMI quantified using Brillouin light spectroscopy in experiment, sizeable DMI seen in Pt/Co/AlOx