Spin Superfluidity and Long Range Transport in Thin-Film Ferromagnets

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Collaborators

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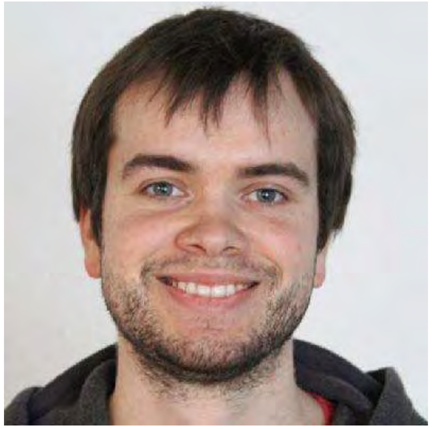


Cecilia Holmqvist

H. Skarsvåg, C. Holmqvist, and A. Brataas, PRL 115, 237201 (2015)

Question

- Can a thin-film ferromagnet behave like a superfluid ?

- New phase-coherent spin-transport properties
- Spin transport without significant losses over long distances
- Low-dissipation
  - Interconnects
  - spin logic devices
  - nonvolatile magnetic memory devices.

Answer

NO

Question 2:

- Can we realize spin superfluidity in other geometries involving ferromagnets ?

Answer

YES

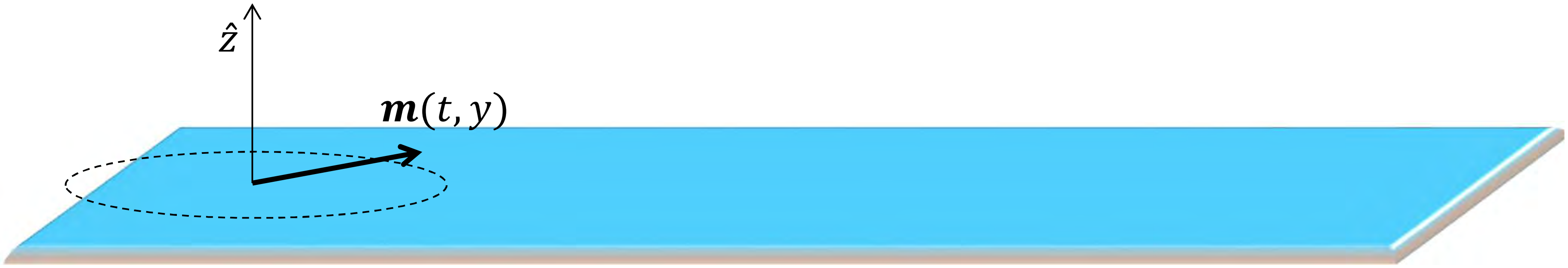
Outline

- Spin superfluidity
- Experimental suggestion
- Results

Spin Superfluidity

- E. B. Sonin, Advanced in Physics 69:3, 181 (2010)
- Ferromagnetic insulator thin film
- Free energy

$$F = A(\nabla\, \boldsymbol{m})^2 + 2\pi M_S^2 (\boldsymbol{m} \cdot \hat{z})^2$$



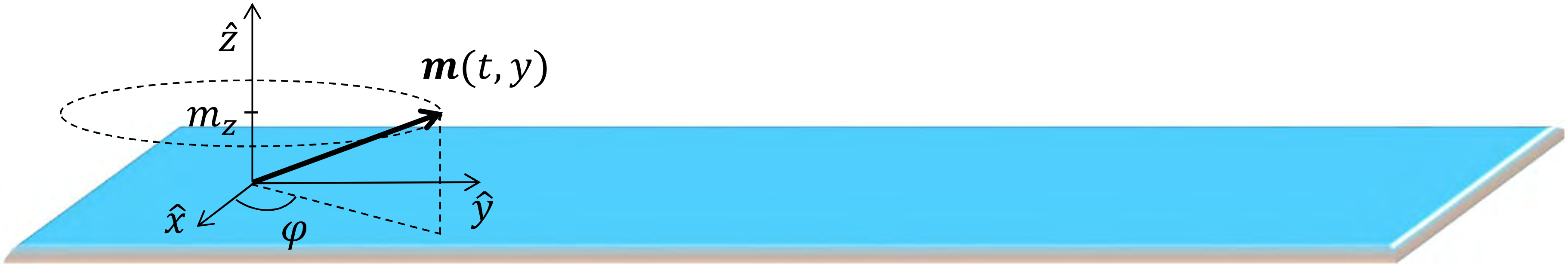
Spin Superfluidity

- Free energy

$$F = A(\nabla\, \boldsymbol{m})^2 + 2\pi M_S^2 (\boldsymbol{m} \cdot\ \hat{z})^2$$

- Magnetization

$$\boldsymbol{m} = (\sqrt{1 - {m_z}^2}\cos(\varphi), \sqrt{1 - {m_z}^2}\sin(\varphi), m_z)$$



Spin Superfluidity

- Free energy

$$F = A(\nabla\,\boldsymbol{m})^2 + 2\pi M_S^2(\boldsymbol{m}\cdot\,\hat{z})^2$$

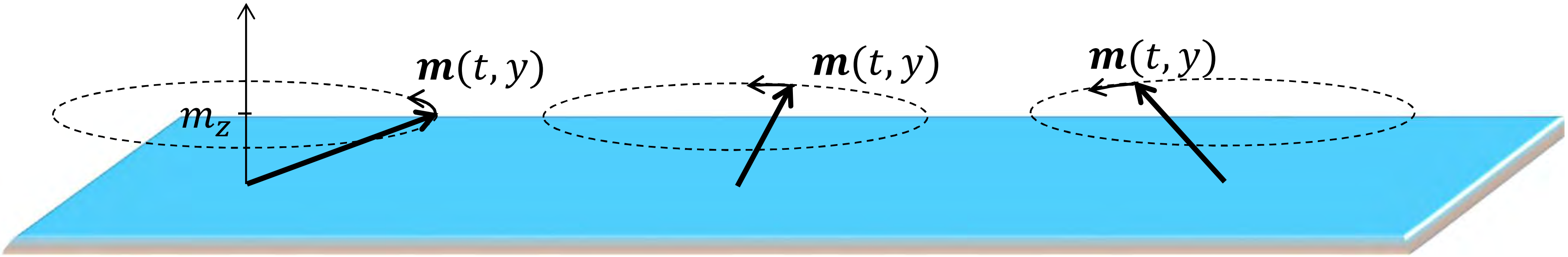
- Magnetization

$$\boldsymbol{m} = \left(\sqrt{1-m_z{}^2}\cos(\varphi), \sqrt{1-m_z{}^2}\sin(\varphi), m_z\right)$$

- Hydrodynamic equations

$$\frac{dm_z}{dt} = -\frac{2A\gamma}{M_S}\nabla^2\varphi; \qquad \frac{d\varphi}{dt} = -4\pi\gamma M_s m_z$$

- Solution $m_z = \text{const.};\quad \varphi(\boldsymbol{r}, t) = \varphi(\boldsymbol{r}) + \Omega t$



Comparison

Spin superfluidity (SSF)	Conventional superfluidity
Out-of-plane component m_z, in-plane angle φ	Superfluid density n, order parameter φ
Hydrodynamic eqs. for m_z and φ	Hydrodynamic eqs. for n and φ
Spin current $J_s \propto \nabla\varphi$	Mass current $J \propto \nabla\varphi$
Linear soundlike spectrum	Linear spectrum of density waves: sound waves
Stability of current-carrying states: Landau criterion	Stability of current-carrying states: Landau criterion

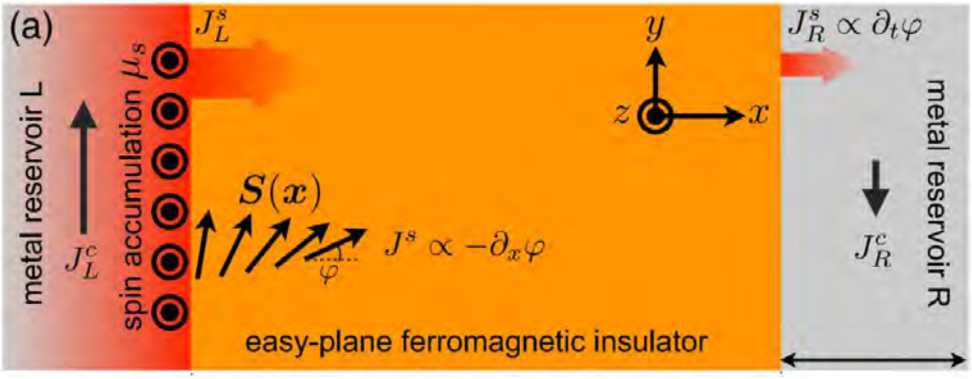
E. B. Sonin, Advances in Physics 59:3, 181 (2010)

Spin Superfluidity in N-FM-N devices

- YIG with Pt leads
- Injection of *z*-polarized spins
- Gilbert damping α

$$\dot{\varphi} = \frac{K}{s} m_z + \alpha\, \dot{m}_z;$$

$$\dot{m}_z = \frac{A}{s} \nabla^2 \varphi - \alpha \dot{\varphi}$$



S. Takei and Y. Tserkovnyak, PRL 112, 227201 (2014)

- Precession frequency

$$\Omega = \frac{\mu_s}{\hbar} \frac{g_L^{\uparrow\downarrow}}{g_L^{\uparrow\downarrow} + g_R^{\uparrow\downarrow} + g_\alpha}$$

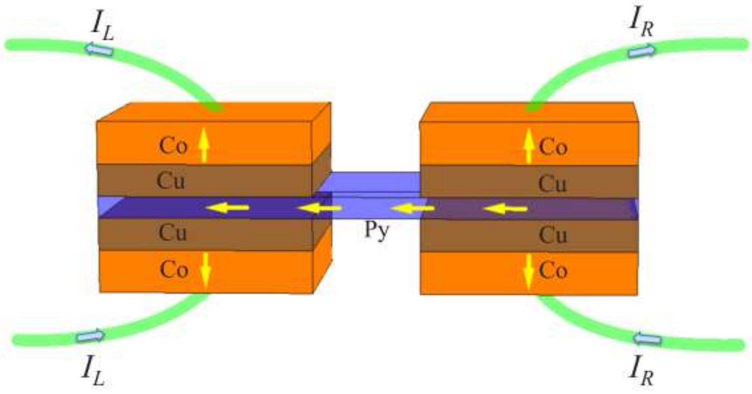
where $g_\alpha = 4\pi\alpha s L/\hbar$

- Spin current

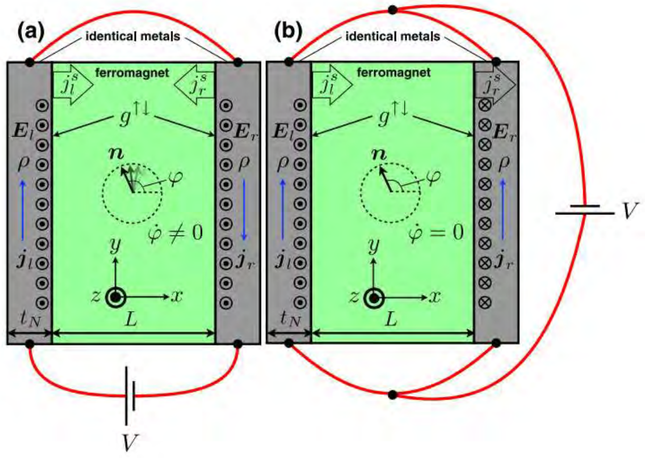
$$J_R^s = \frac{\mu_s}{4\pi} \frac{g_L^{\uparrow\downarrow} g_R^{\uparrow\downarrow}}{g_L^{\uparrow\downarrow} + g_R^{\uparrow\downarrow} + g_\alpha}$$

Spin Superfluidity in N-FI-N Systems

- Chen et al (PRB’14)
  - Easy-plane and in-plane anisotropy
  - Precession vs. Pinning



- Takei&Tserkovnyak
  - Non-local magnetoresistance PRL’15



Will it Work

NOT, REALLY

Why Not ?

- Missing physics
  - The total dipole-dipole interaction
- Scaling
  - Exchange interaction

$$F \sim k^2 \sim 1/r^2$$

  - Dipole-dipole interaction

$$F \sim k \sim 1/r$$

- Dipole-dipole interaction dominates long-range physics

Dipole-Dipole Interaction

- The dipole-dipole interaction is important for spin superfluidity

$$H_{\text{dip}} = H_{\text{dip}}^{(\text{stat})} + H_{\text{dip}}^{(\text{dyn})}$$

Static demagnetization field

dynamical dipole field

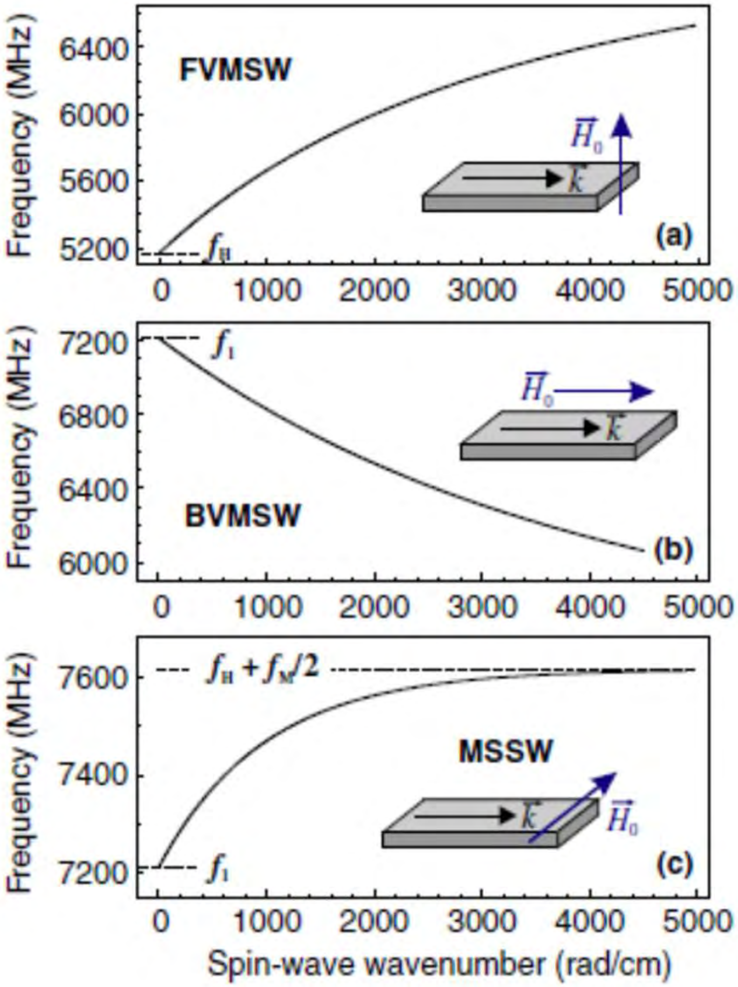
- The static demagnetization field (easy-plane anisotropy)

$$H_{\text{dip}} = -4\pi M_s m_z \hat{z}$$

- The dynamical dipole field
  - Qualitatively changes the low-energy dispersion relation
  - Kalinikos and A. N. Slavin, J. Phys. C: Solid State Phys. 19, 7013 (1986)
- The dynamical dipole field equally important for spin superfluidity

Spin-wave in Thin-Film Ferromagnets

- Low-energy spin-waves
  - Dominated by dipole-dipole interaction
  - Anisotropic dispersion relation
- FVMSW
  - Forward Volume MagnetoStatic Spin-Waves
- BVMSW
  - Backward Volume MagnetoStatic Spin-Waves
- MSSW
  - Magnetostatic Surface Spin-Waves

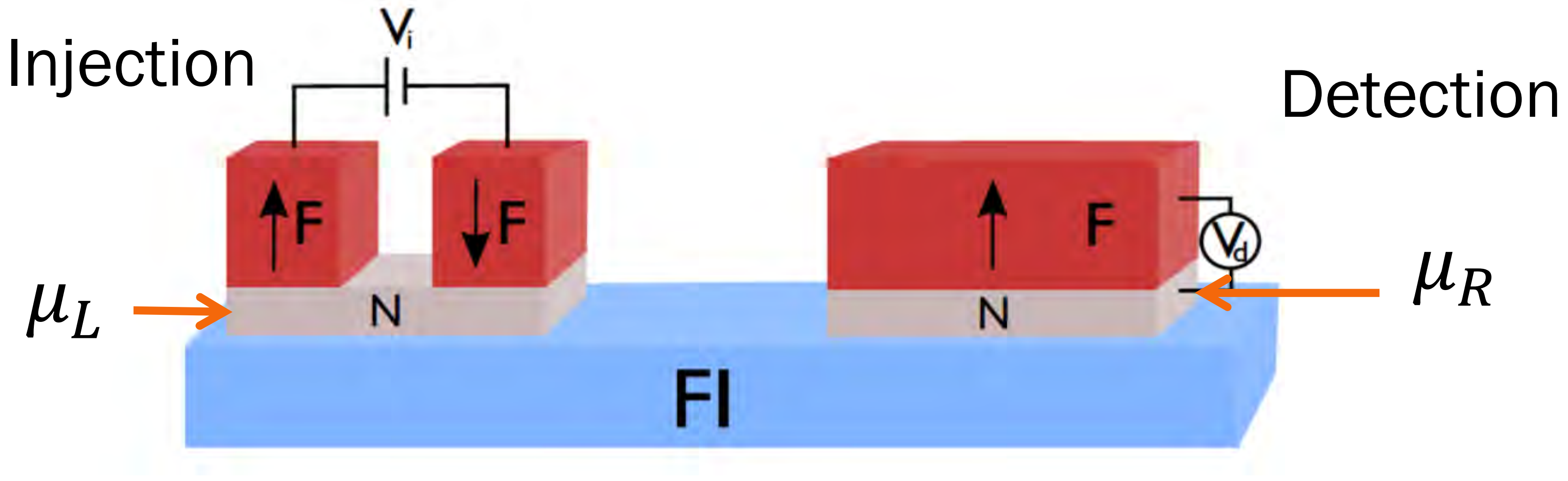


Long Range Spin Transport: Two Challenges

- 1: Decay of spin signal due to Gilbert damping
- 2: Strong dipole-dipole interaction

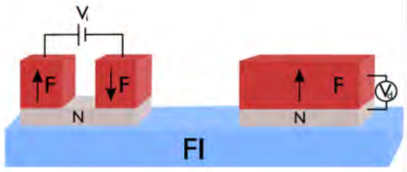
Solving Challenge 1: Proposed Setup

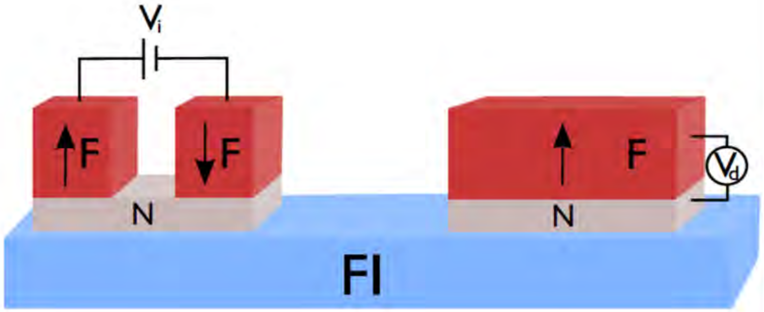
- Apply out-of-plane polarized spin accumulation to thin film (left)
- Induce 2π magnetization rotations in-plane
- Measure spin current via spin-pumping (right)



Length Dependence of Spin Signal

- Output signal μ_R depends on $A_{in(out)/}V$





- By scaling injector/detector area with distance
  - No length dependence of spin signal
- Extremely long-range spin transport without any losses

Challenge 2: Dipole-Dipole Interaction

- LLGS equation

$$\dot{\mathbf{m}} = -\gamma \mathbf{m}\times\mathbf{H}_{\text{eff}} + \alpha\mathbf{m}\times\dot{\mathbf{m}} + \boldsymbol{\tau}_{\text{STT}}$$

- Effective magnetic field

$$\mathbf{H}_{\text{eff}} = \mathbf{H}_{\text{ext}} + \mathbf{H}_{\text{dip}} = (2A/\mathrm{M}_s)\nabla^2 m - 4\pi M_s m_z \mathbf{z} + \mathbf{H}_{\text{dip}}^{(\text{dyn})}$$

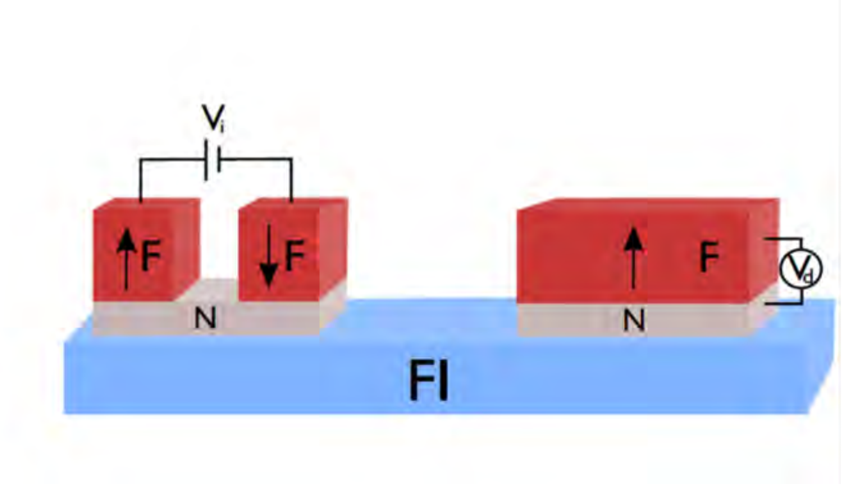
- Spin-transfer torque

$$\boldsymbol{\tau}_{\text{STT}} = -(\alpha'/\hbar)\mathbf{m}\times\mathbf{m}\times\boldsymbol{\mu}$$

- Damping

$$\alpha = \alpha_0 + \alpha'$$

Intrinsic Gilbert damping



Numerical Approach

- Solve the spatiotemporal LLG using RK4 and MuMax3
- Calculate

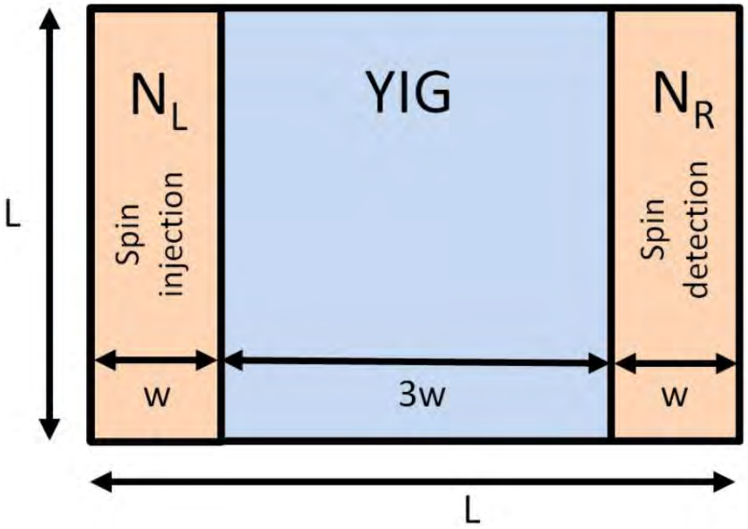
$$\boldsymbol{\mu}_R \sim \hbar \left\langle \mathbf{m} \times \dot{\mathbf{m}} \right\rangle_z$$

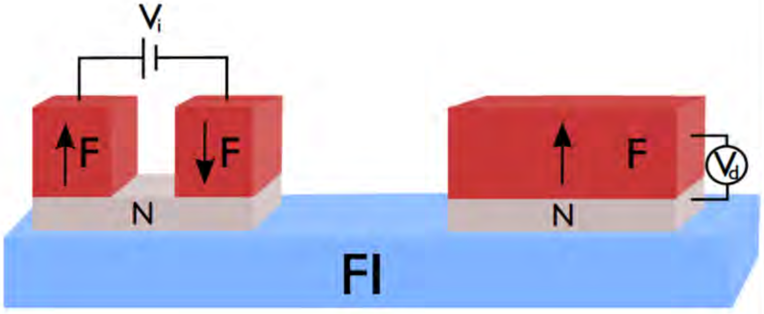
as a function of

$$\boldsymbol{\mu}_L$$

and

$$L$$

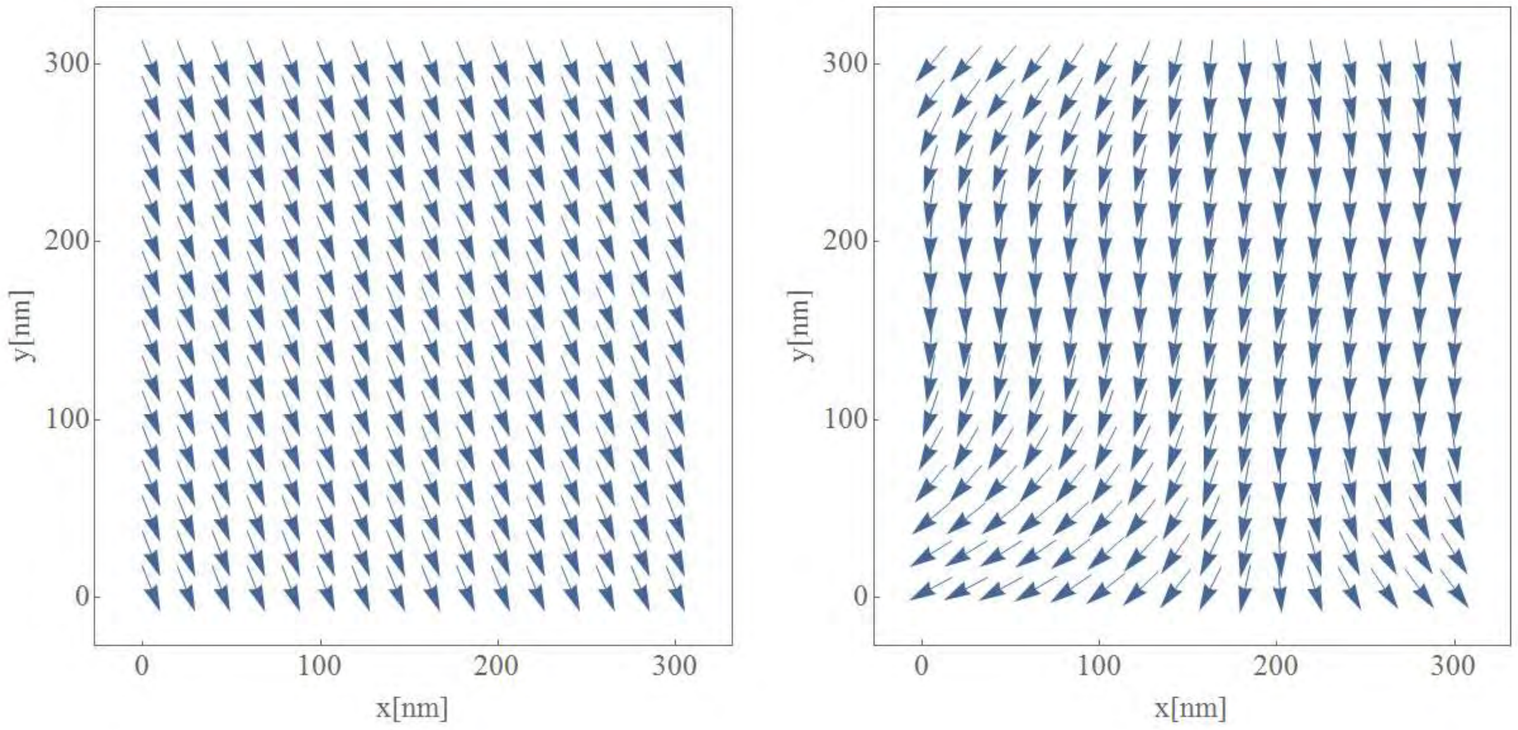




Example of Numerical Results

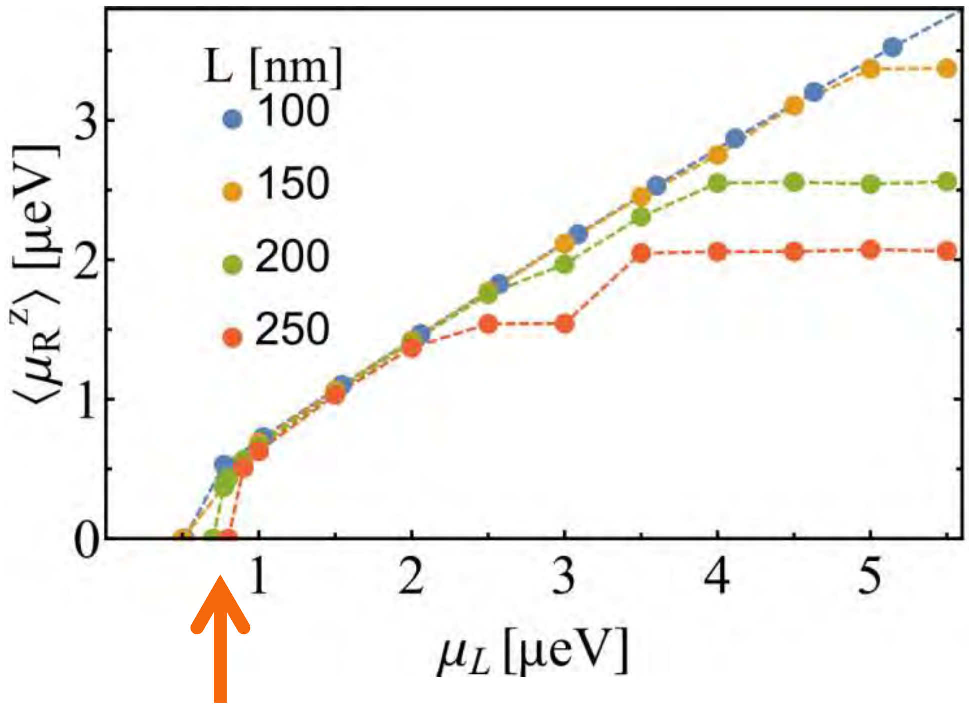
Without dipole field

With dipole field



length L=300 nm; thickness d=5 nm; # of points N^2=4225

Results – Square Sample



Shape anisotropy - pinning

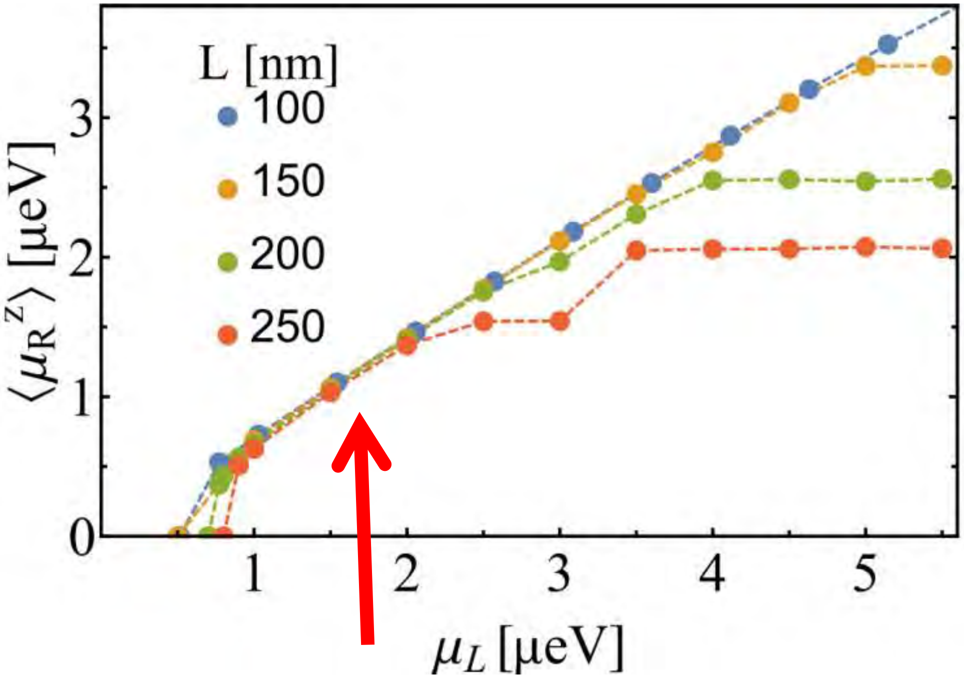
Threshold, μ_L^{thr}

H. Chen, A. D. Kent, A. H. MacDonald and I. Sodemann, PRB 90, 220401 (2014)

$g^{\perp}_{L/R} = 5 \cdot 10^{14}\mathrm{cm}^{-2}\mathrm{e}^{-2}/\mathrm{h}$
$\alpha_0 = 1 \cdot 10^{-3}$
$A = 3.7 \cdot 10^{-7}$ erg/cm

$4\pi M_S = 1750$ G
$d_{YIG} = 5$ nm

Results – Square Sample

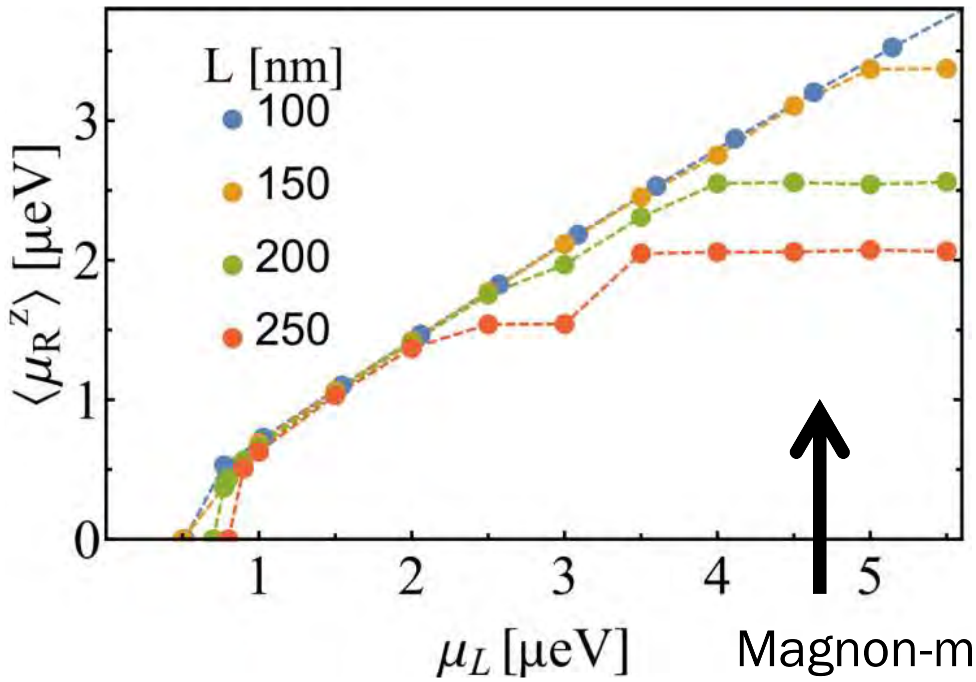


Spin superfluidity!!

Ideal behavior:

- Linear increase as function of μ_L
- Constant as function of L

Results – Square Sample



Magnon-magnon interaction

Saturation, μ_L^{sat}
Squeezing:

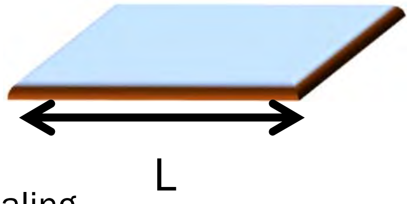
- SSF for $\mu_L^{thr} < \mu_L < \mu_L^{sat}$
- no SSF for $\mu_L^{sat} < \mu_L^{thr}$

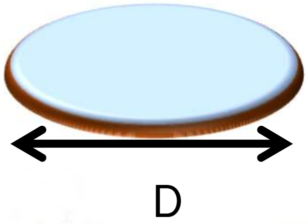
Can We Do Better

Problem

Solution

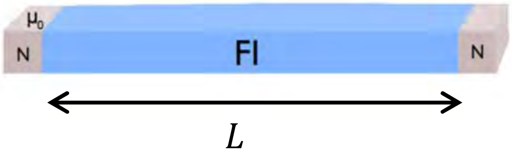
1. Shape anisotropy → pinning

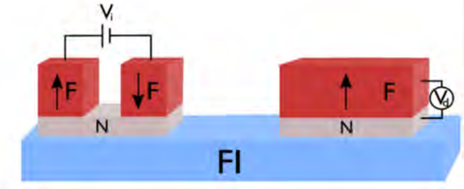




Solved! ☺

2. Scaling



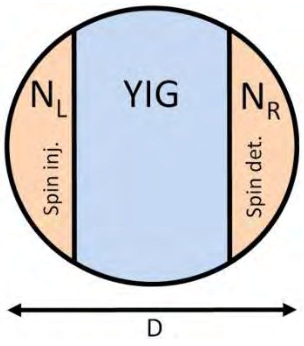


Solved! ☺

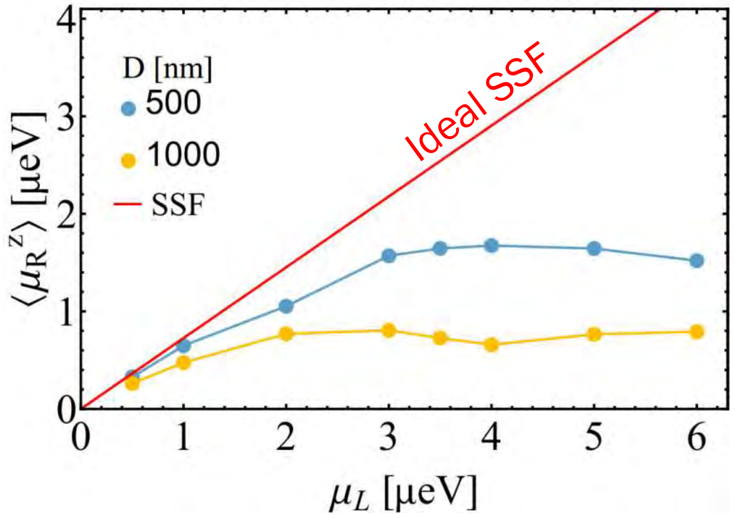
resistance $r_\alpha \propto L\alpha_0$

$r_\alpha \propto \frac{V}{A_{contact}}$ → infinite scaling!

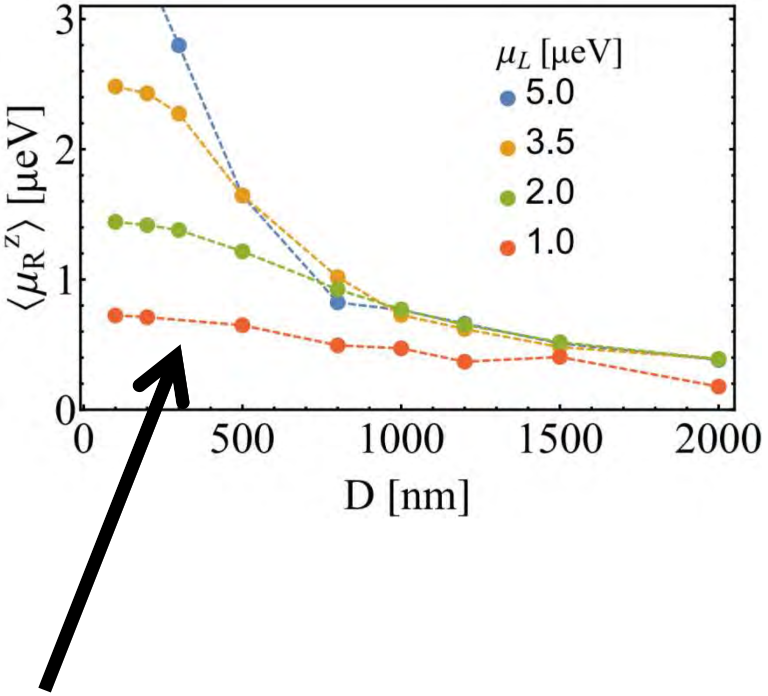
Results - Disk



Constant size



Constant spin accumulation



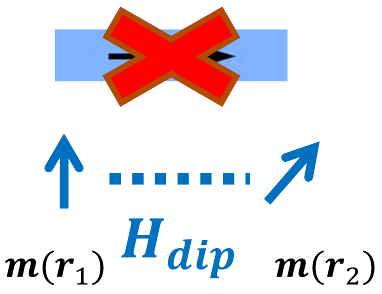
- No pinning, μ_L^{th} =0
- Still squeezing effect
- Long-range transport,
  but with lower efficiency than SSF:
  ~80% drop over interval D=100 nm – 2 μm

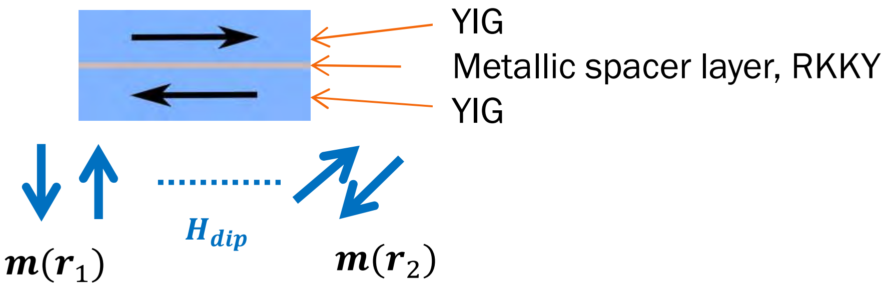
Can We Do Better?

Problem

Solution

3. Dipole field: $\boldsymbol{h} = 4\pi M_s \int \hat{G}(\boldsymbol{r}-\boldsymbol{r}')\boldsymbol{m}(\boldsymbol{r}')$





Ideal SSF in this configuration:

Magnetizations: $\boldsymbol{m}_{1/2} = \left(\pm\sqrt{1-m_{1/2,z}^2}\,\cos\varphi_{1/2}\,, \pm\sqrt{1-m_{1/2,z}^2}\,\sin\varphi_{1/2}\,, m_{1/2,z}\right)$

Layer coupling: $\omega_{E,1(2)} = \gamma J/d_{2(1)}M_{s,2(1)}$

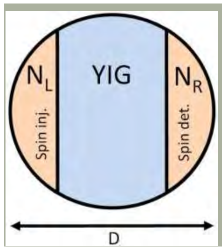
Hydrodynamic eqs.: $\dot{m}_{1,z} = \frac{2\gamma A}{M_{s,1}}\nabla^2\varphi_1 - \alpha_1\,\dot{\varphi}_1;\qquad \dot{\varphi}_1 = [4\pi M_{s,1}\gamma + \omega_{E,1}]m_{1,z} + \omega_{E,1}m_{2,z} + \alpha_1\,\dot{m}_{1,z}$

Out signal: $< \mu_R^z > = -\hbar\Omega;$

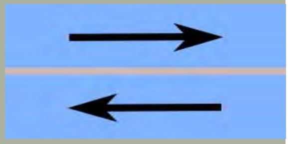
$m_z = -\Omega/(2\omega_E + 4\pi M_{s,1}\gamma)$ with $\omega_{E,1} = \omega_{E,2} = \omega_E$

$(\varphi_1 - \varphi_2)\sim\alpha_2\Omega/\omega_E$

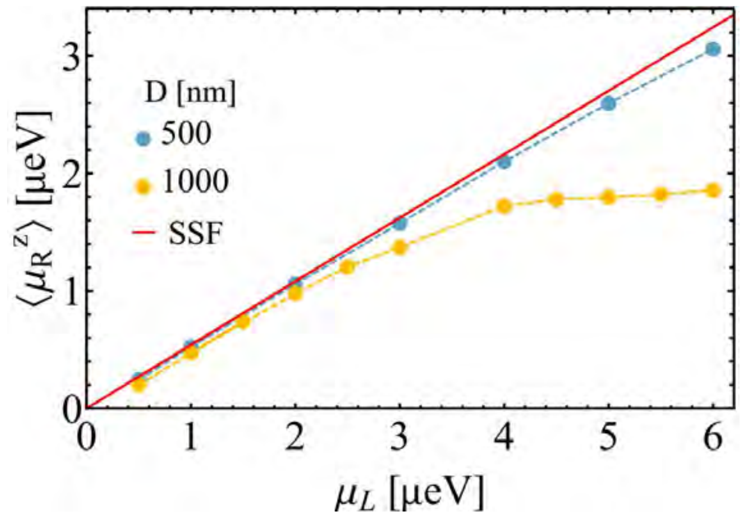
…. YES!

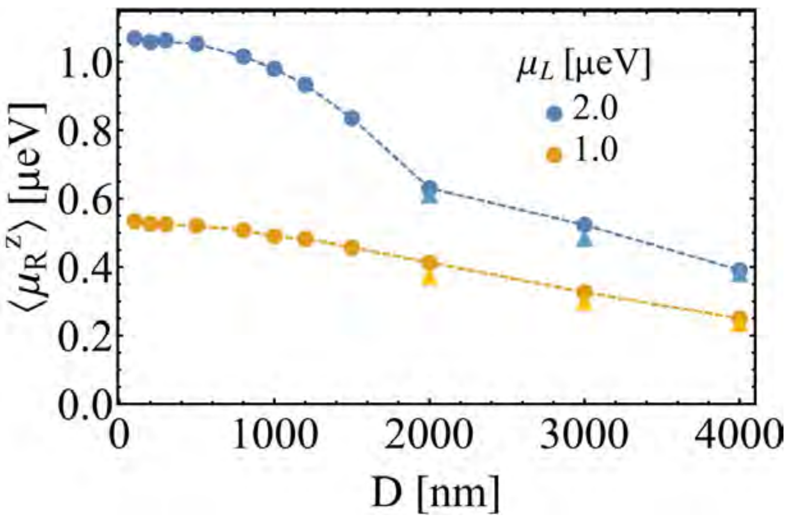


Results – Trilayer Disk



- No pinning
- Weaker saturation effect
- Spin superfluidity for larger $\boldsymbol{\mu}_L$ and L
- Gradual transition to long-range transport





Conclusions

- A single thin-film ferromagnet does not exhibit long-range superfluid spin transport
- The inclusion of the dipole interaction qualitatively changes spin transport
- Long-range superfluid transport in trilayer FI-NM-FI systems

	Square (□)	Disk (◯)	Tri-layer disk (◯)
Pinning	Yes	No	No
SSF	$L < 300$ nm $\mu_L = 1 - 2\ \mu$eV	$D < 500$ nm $\mu_L = 1 - 2\ \mu$eV	$D\ < 1\ \mu$m $\mu_L\ = 1\ \mu$eV
Long-range spin transport	No	Up to $D \sim 1\ \mu$m	Longer than $D \sim 4\ \mu$m

H. Skarsvåg, CH, A. Brataas, PRL 115, 237201 (2015)

Acknowledgements

EU FP7 FET *InSpin*

ERC AdG *Insulatronics*

Dipole-Dipole Interaction

- Spin superfluidity occurs in the long wavelength limit
  - The dipole-dipole interaction is important for spin superfluidity
- Maxwell’s equations

$$\nabla \times \mathbf{H}_{\mathrm{dip}} = 0, \quad \nabla \bullet \left(\mathbf{H}_{\mathrm{dip}} + 4\pi M_s \mathbf{m} \right) = 0$$

- Solution

$$\mathbf{H}_{\mathrm{dip}}(\mathbf{r}t) = 4\pi M_s \int d\mathbf{r}' \int dt' G(\mathbf{r}t, \mathbf{r}'t') m(\mathbf{r}'t')$$

$$= \text{-}4\pi M m_z \mathbf{z} + H_{\mathrm{dip}}^{(\mathrm{dyn})}(\mathbf{r}t)$$

Static demagnetization field

dynamical dipole field