Superfluidity and spin superfluidity
(in spinor Bose gases and magnetic insulators)

Rembert Duine

Institute for Theoretical Physics, Utrecht University

Department of Applied Physics, Eindhoven University of Technology

Nature Physics 11, 1022–1026 (2015), Phys. Rev. Lett. 116, 117201 (2016), arXiv:1603.01996 [cond-mat.quant-gas], arXiv:1604.03706 [cond-mat.mes-hall]

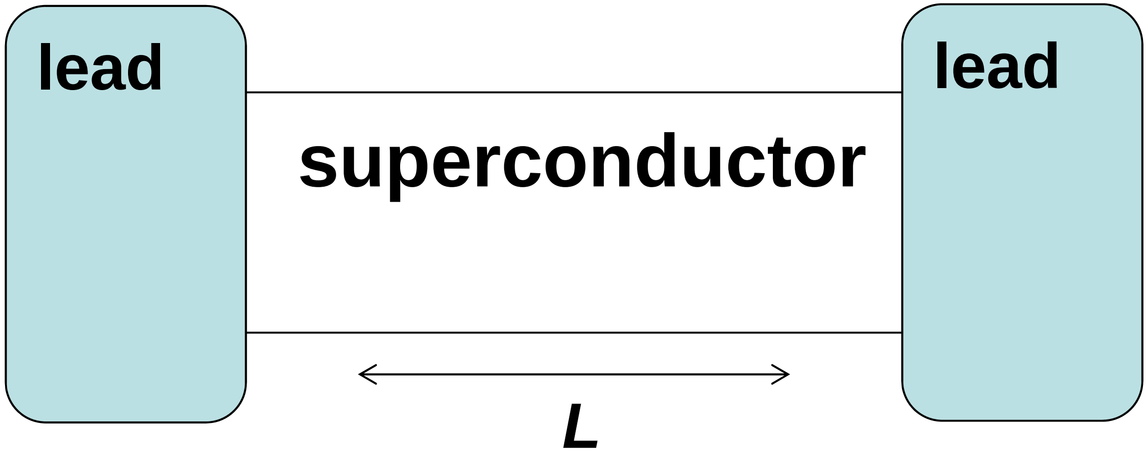
Collaborators

Utrecht:
Benedetta Flebus
Kevin Peters
Gerrit Bauer (also Delft/Sendai)

Other:
Jogundas Armaitis (Vilnius)
Ludo Cornelissen, J. Liu,
Bart van Wees (Groningen)
Yaroslav Tserkovnyak, *Scott Bender* (UCLA->UU)
J. Ben Youssef (Brest), Arne Brataas (NTNU)

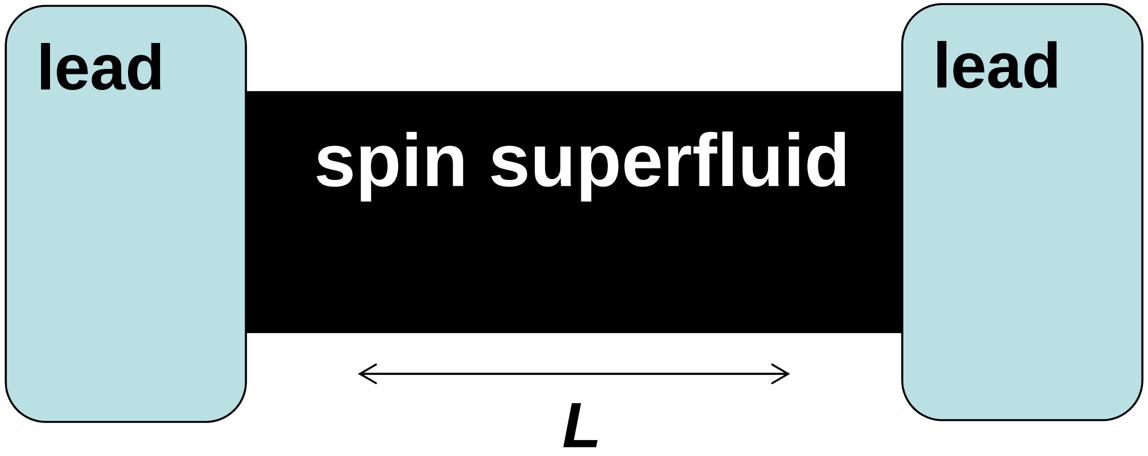
FOM
NWO Netherlands Organisation for Scientific Research
Delta Institute for Theoretical Physics
erc European Research Council

Long-term motivation



$I=V/R$ with
R independent of L

below room T



?

above room T?

Outline

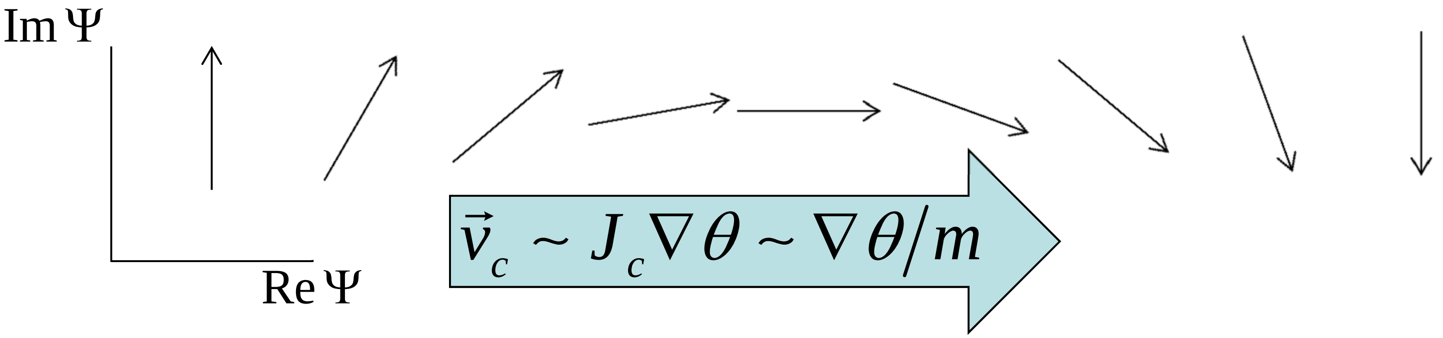
- Introduction superfluidity and spin superfluidity

- Spinor gases: combining superfluidity and spin superfluidity (theory)

- Spin transport through magnetic insulators (theory and experiment)

Superfluid (mass) transport

Superfluid *U(1)* order parameter: $\Psi = \sqrt{\rho_c}\, e^{i\theta}$



$$\vec{v}_c \sim J_c \nabla\theta \sim \nabla\theta / m$$

$$\frac{\partial \rho_c}{\partial t} = -\nabla \cdot \vec{j}_c$$

+

supercurrent: $\vec{j}_c = \rho_c \vec{v}_c$ **carried by condensate**

$$\frac{\partial \theta}{\partial t} = -\frac{\mu}{\hbar}$$

chemical potential μ

Wave-like excitations:

$$\omega \sim \sqrt{J_c \left(\partial\mu / \partial\rho\right) k}$$

stiffness

interactions $\propto g\rho_c$

If ρ_c **zero then** $\omega \sim J_s k^2$

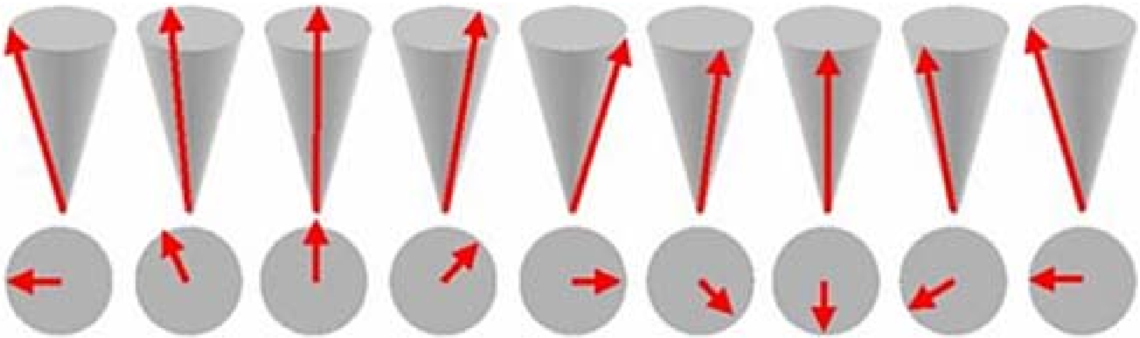
(ballistic transport)

Halperin/Hohenberg (1969)

(ballistic) spin transport

Magnetic insulator (exchange only)

$$H = -J_{xc} \sum_{\langle i,j \rangle} \vec{S}_i \cdot \vec{S}_j$$



Landau-Lifschitz equation:

$$\hbar \frac{d\vec{S}_i}{dt} = J_{xc} \vec{S}_i \times \left(\sum_{j \in \text{ neigbours } i} \vec{S}_j \right) \sim J_{xc} \vec{S} \times \nabla^2 \vec{S} = -\nabla \cdot \vec{j}$$

spin current:

$$\vec{j}_\alpha \sim J_{xc} \vec{S} \times \partial_\alpha \vec{S}; \;\; \alpha \in \{x, y, z\}$$

particle-like excitations: $\omega \sim J_{xc} k^2$ **spin waves/magnons**

Halperin/Hohenberg (1969); review: Sonin (2010)

Spin superfluidity (I)

Easy-plane magnetic insulator [SO(3) -> U(1)]

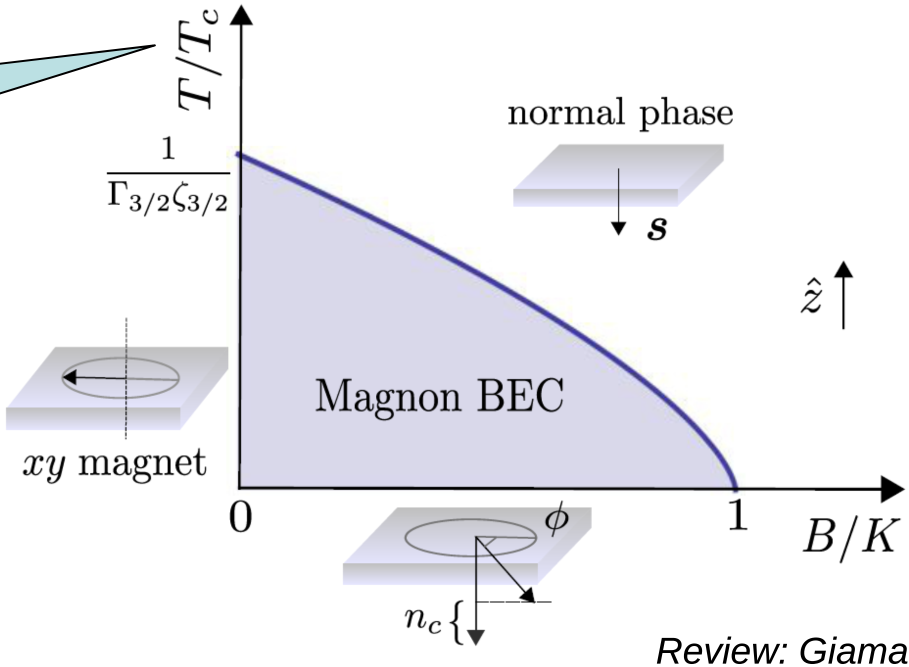
$$H = -J_{xc}\sum_i \vec{S}_i \cdot \left(\vec{S}_{i-1} + \vec{S}_{i+1}\right) + K\sum_i \left(S_i^z\right)^2 + B\sum_i S_i^z$$

exchange **anisotropy** **field**

$$T_{BEC} \sim k_B J_{xc}\left(1 - B/K\right)^{2/3}$$

Holstein-Primakoff trafo:

$$\vec{S} \sim \begin{pmatrix} \sqrt{2}\left(\mathrm{Re}\langle \hat{a}\rangle\right) \\ \sqrt{2}\left(\mathrm{Im}\langle \hat{a}\rangle\right) \\ \langle \hat{a}^\dagger \hat{a}\rangle - 1 \end{pmatrix}$$



Review: Giamarchi (2008)

Halperin/Hohenberg (1969); Koenig et al. (2001); review: Sonin (2010)

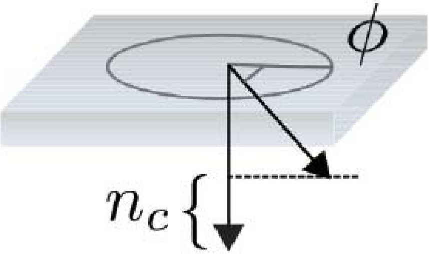
Spin superfluidity (II)

Zero *T* dynamics governed by Landau-Lifshitz equation:

$$\hbar \frac{d\vec{S}}{dt} = J_{xc} \vec{S} \times \left[\nabla^2 \vec{S} + K S^z \hat{z} + B \hat{z} \right]$$

Write:

$$\vec{S} \sim \begin{pmatrix} \sqrt{2n_c} \cos\phi \\ \sqrt{2n_c} \sin\phi \\ n_c - 1 \end{pmatrix}$$



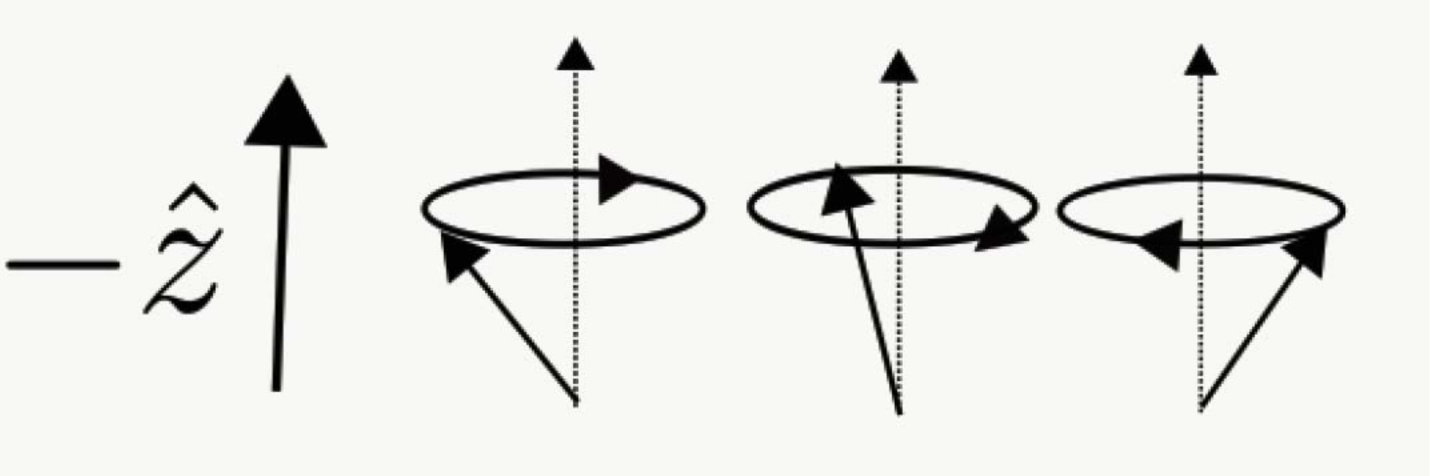
$$\frac{\partial n_c}{\partial t} \sim J_{xc} n_c \nabla^2 \phi \equiv -\nabla \cdot \vec{j}_s$$

$$\frac{\partial \phi}{\partial t} \sim B - K + K n_c \equiv \mu / \hbar$$

Same as equations for mass superfluid!

$$\omega \sim \sqrt{J_{xc} K n_c} k$$

Spin superfluidity (III)



$j_{s,\alpha} \sim J_{xc} n_c \partial_\alpha \phi$; polarization in z-direction

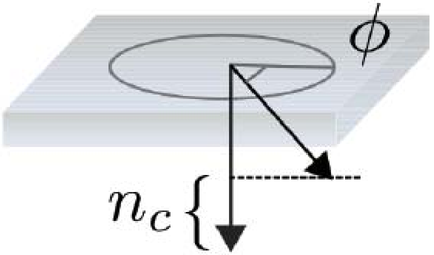
Halperin/Hohenberg (1969); review: Sonin (2010)

Mass vs. spin superfluidity

- mass current j_c
- phase of superfluid order parameter θ
- superfluid stiffness J_s
- interparticle interactions g

$$\Psi = \sqrt{\rho_c}\, e^{i\theta}$$

- spin current j_s
- in-plane angle of magnetization ϕ
- exchange interactions J_{xc}
- easy-plane anisotropy K



Outline

- Introduction superfluidity and spin superfluidity

- Spinor gases: combining superfluidity and spin superfluidity (theory)

- Spin transport through magnetic insulators (theory and experiment)

Related work

- **Our work: hydrodynamic description treating spin and mass superfluidity on equal footing**

- **Spin currents in spinor gases:**
  - K. Kudo and Y. Kawaguchi, Physical Review A **84**, 043607 (2011).
  - H. Flayac, *et al*., Physical Review B **88**, 184503 (2013).
  - Q. Zhu, Q.-f. Sun, and B. Wu, Phys. Rev. A **91**, 023633 (2015).

- **Stability of spirals:**
  - R. W. Cherng, *et al*., Phys. Rev. Lett. **100**, 180404 (2008).

- **Magnon condensation:**
  - Fang, *et al*., Phys. Rev. Lett. **116**, 095301 (2016) – tonight's evening talk (?).

- **Reviews:**
  - Y. Kawaguchi and M. Ueda, Physics Reports **520**, 253 (2012).
  - D. M. Stamper-Kurn and M. Ueda, Rev. Mod. Phys. **85**, 1191 (2013).

Questions

- **Which system is both a mass and spin superfluid?**
- **What is the interaction between mass and spin superfluidity in such a system?**

NB: a ferromagnetic mass superfluid

$$\neq$$

spin superfluid

Ferromagnetic spinor Bose with quadratic Zeeman effect

We have hamiltonian:

field

easy-plane anisotropy

leads to Bose condensation

g_1<0, leads to ferromagnetism

$$\hat{H} = \int d\vec{x}\hat{\psi}^{\dagger}\left[-\frac{\hbar^2\nabla^2}{2m} - BF^z - K\left(F^z\right)^2\right]\hat{\psi} + g_0\left(\hat{\psi}^{\dagger}\hat{\psi}\right)^2 + g_1\left(\hat{\psi}^{\dagger}\vec{F}\hat{\psi}\right)^2$$

Deep in ferromagnetic regime, zero T linearized mean-field equations reduce to equations for uncoupled mass and spin superfluid with:

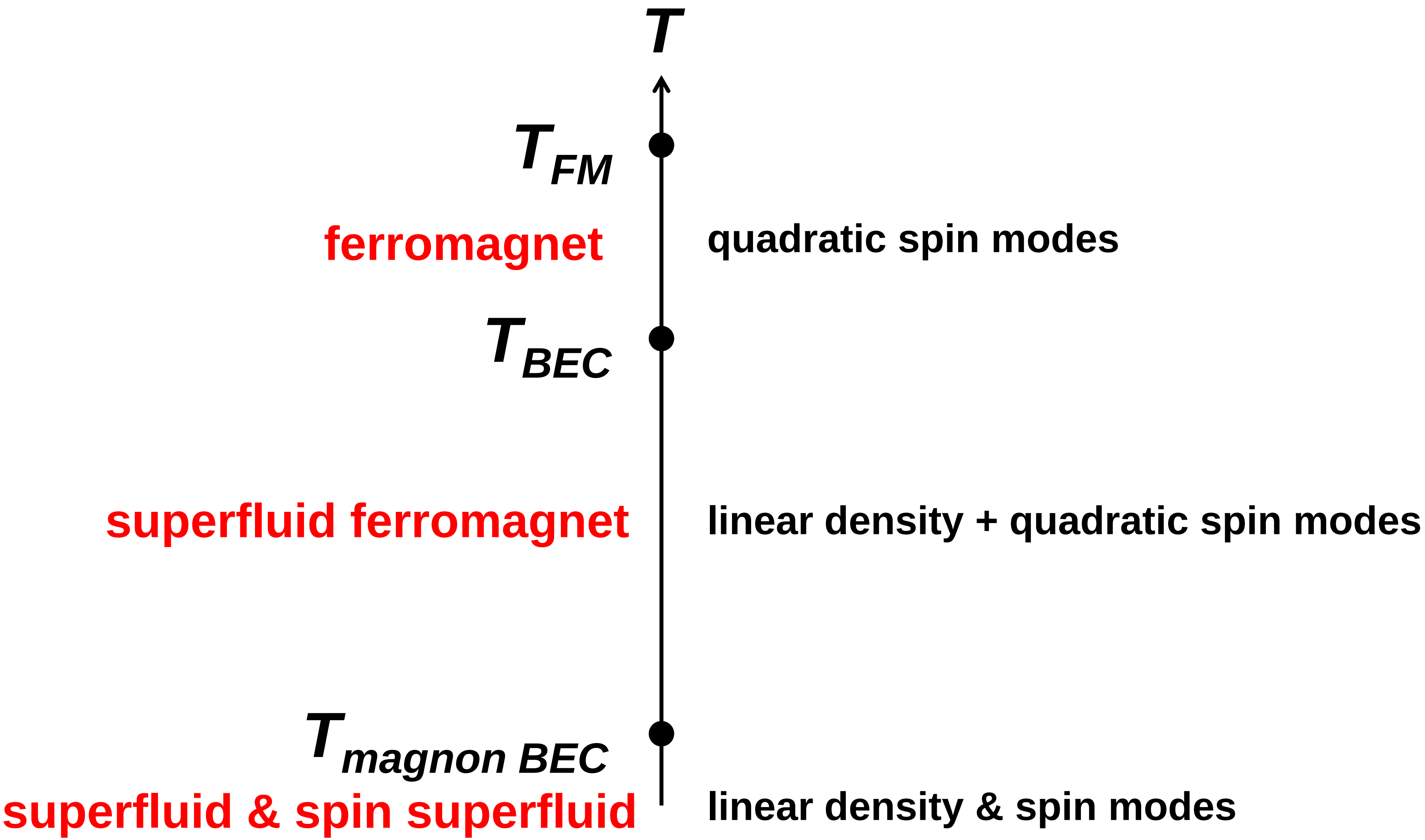
Superfluid and spin stiffness: $J_s \sim J_{xc} \sim \hbar/m$

Collective modes:

$$\omega_{mass} \sim \sqrt{\hbar\rho_c\left(g_0+g_1\right)/mk} \qquad \omega_{spin} \sim k\sqrt{\frac{\hbar K\left(K-B\right)}{m}}$$

Armaitis and RD, arXiv (2016)

Collective (Goldstone) modes



T

T_{FM}

ferromagnet — **quadratic spin modes**

T_{BEC}

superfluid ferromagnet — **linear density + quadratic spin modes**

$T_{magnon\ BEC}$

superfluid & spin superfluid — **linear density & spin modes**

Coupling between spin and mass superfluid

Occurs via hydrodynamic derivative:

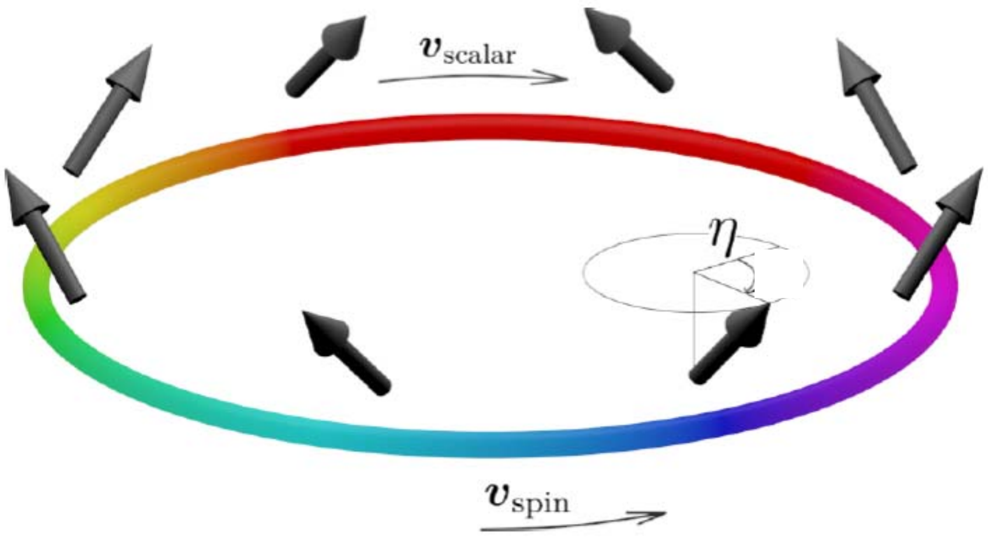
$$\frac{\partial}{\partial t} \rightarrow \frac{\partial}{\partial t} + \vec{v} \cdot \nabla \text{ with } \vec{v} = \frac{\hbar}{m}\left(\nabla \theta - n_z \nabla \phi\right)$$

Influence of spin polarized mass current on magnetization dynamics: “spin transfer”

Current driven by magnetic texture

Armaitis and RD, arXiv (2016)

Stationary solutions



Stationary solutions possible if:

$$\theta' = \frac{n_z}{2}\left(\phi' + \frac{K}{J_s \phi'}\right)$$

Armaitis and RD, arXiv (2016)

Discussion

- Dipolar interactions (lower critical current)
- Upper critical current
- Quasi-equilbrium magnon condensation
- Magnon kinetics
- Coupling to nematic/antiferromagnetic order

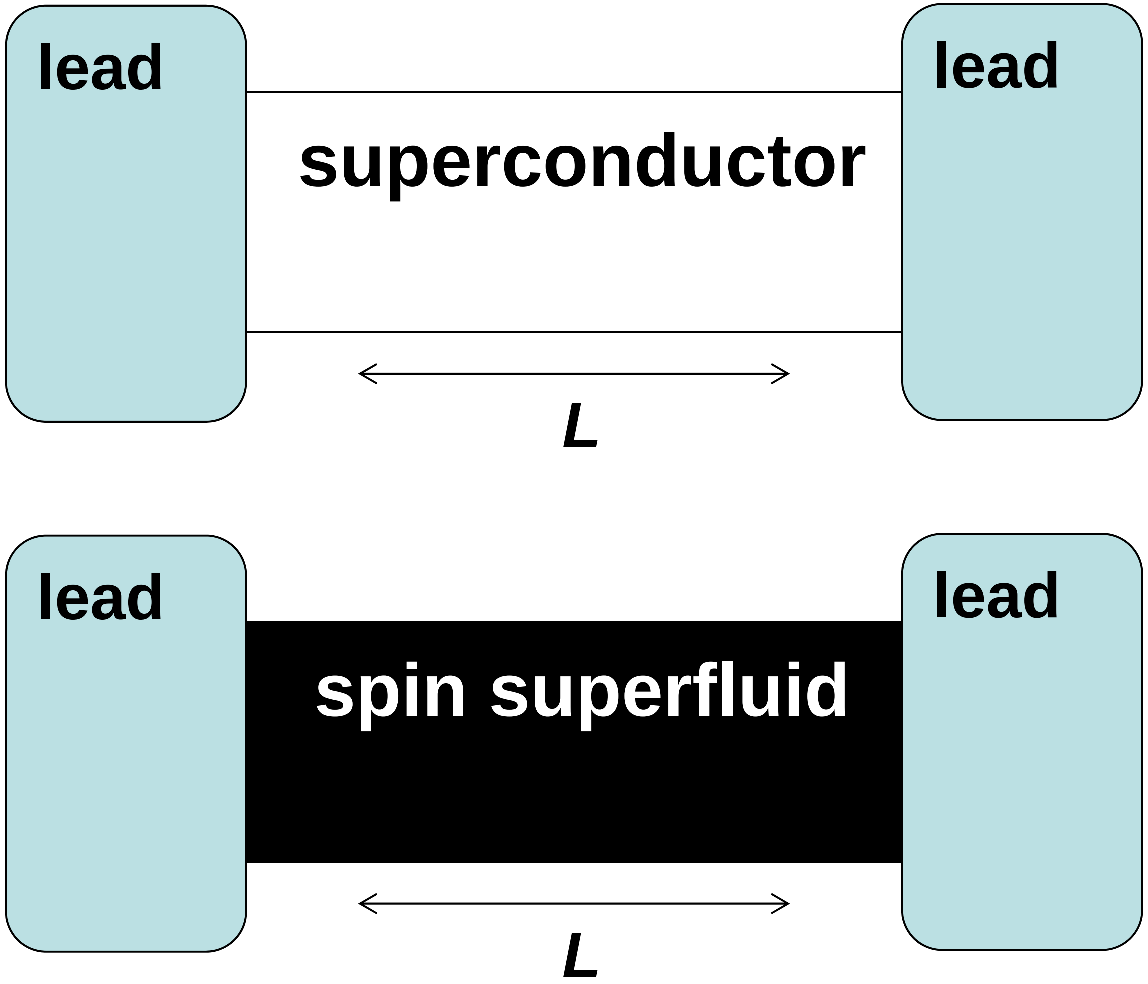
Outline

- Introduction superfluidity and spin superfluidity

- Spinor gases: combining superfluidity and spin superfluidity (theory)

- **Spin transport through magnetic insulators (theory and experiment)**

Long-term motivation



lead

superconductor

lead

L

$I=V/R$ with
R independent of L

below room T

lead

spin superfluid

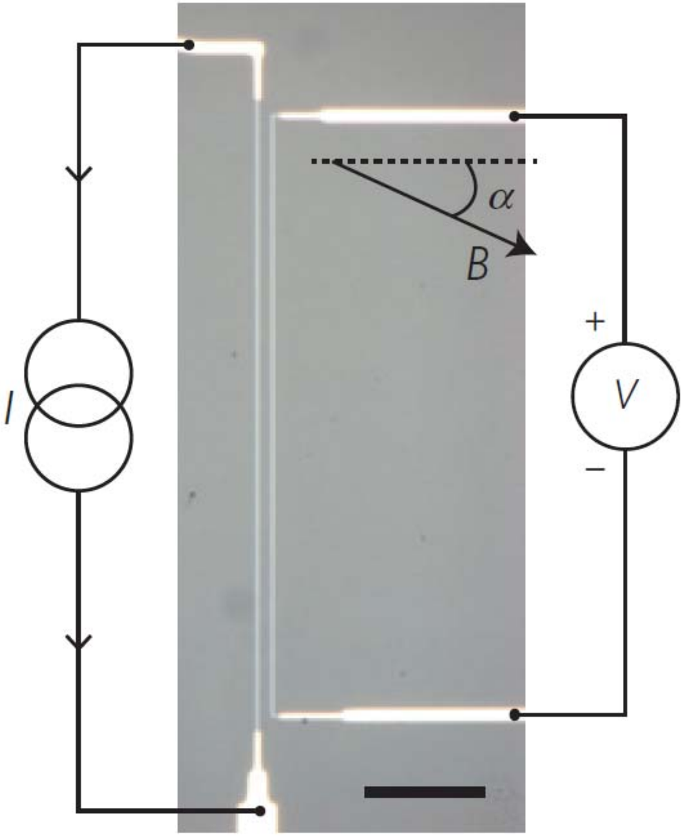
lead

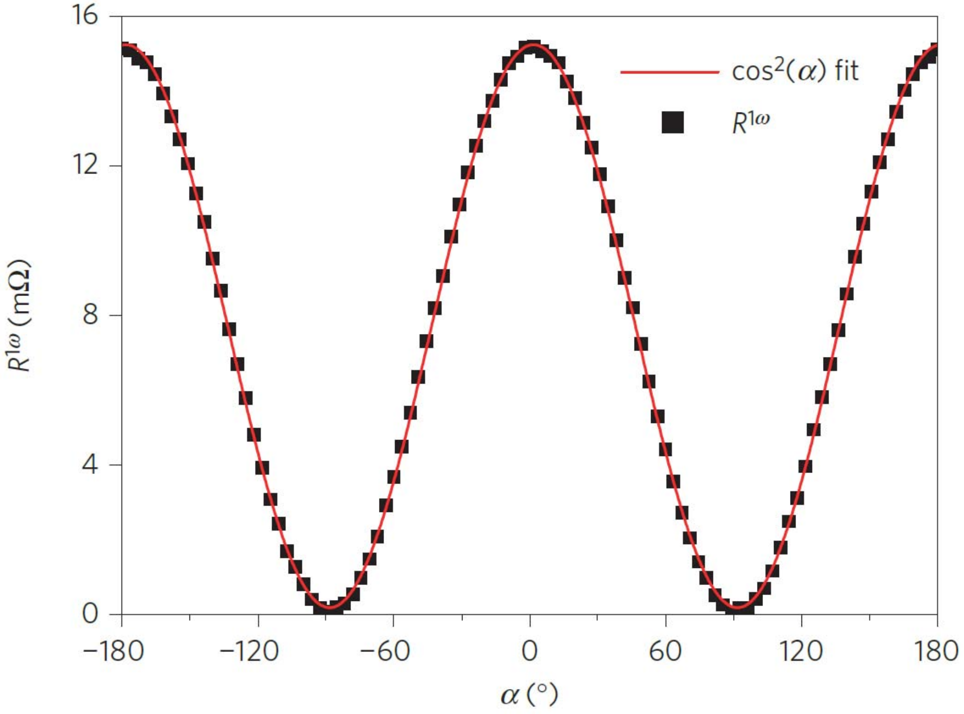
L

?

above room T?

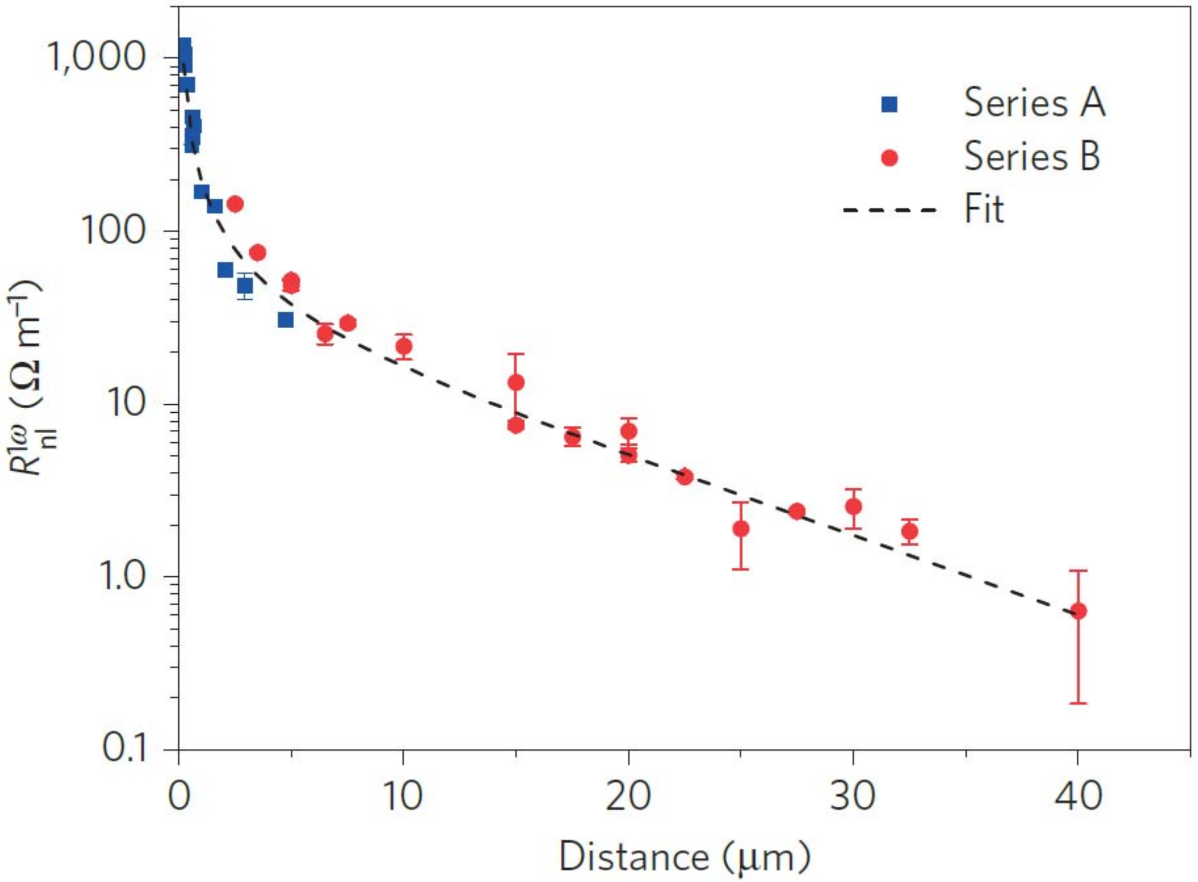
Experiment (I)





- **Pt strips on magnetic insulator Yttrium-Iron-Garnett (YIG)**
- **Non-local (“drag”) resistance $R_D = V/I$**
- **Room *T***

Experiment (II)



- **Short distance: 1/distance**
- **Long distance: exponential decay (length scale 10 μm)**

Idea

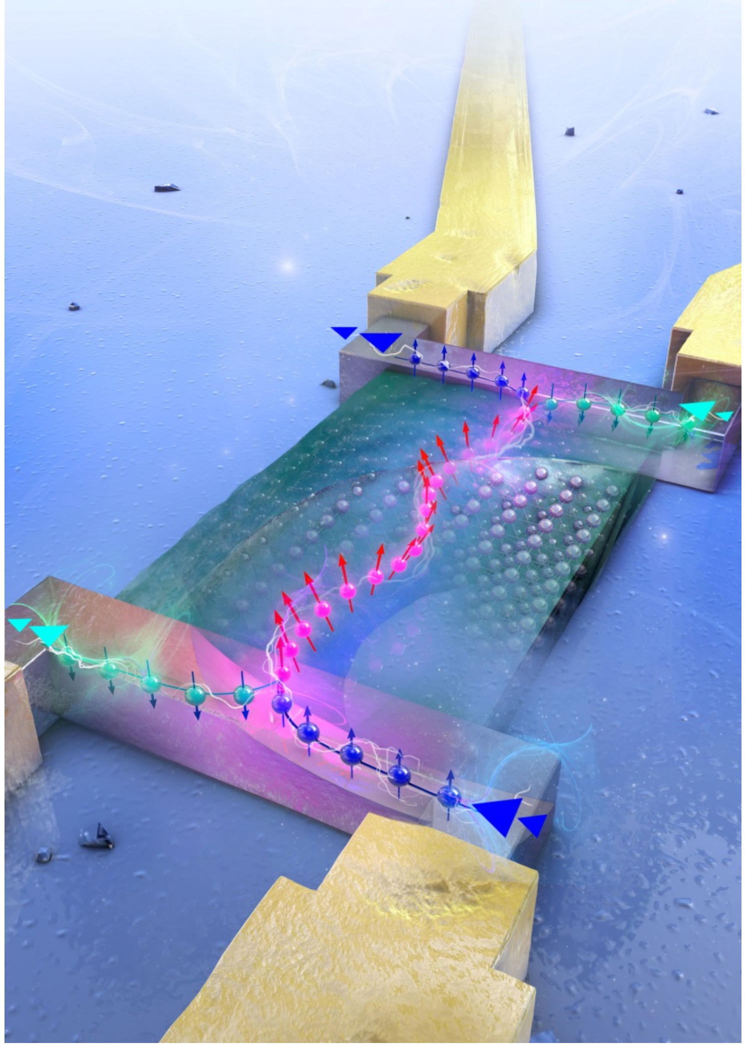


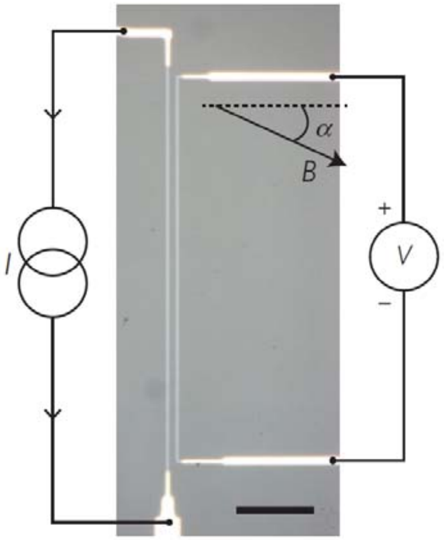
Image courtesy Ludo Cornelissen and Bart van Wees

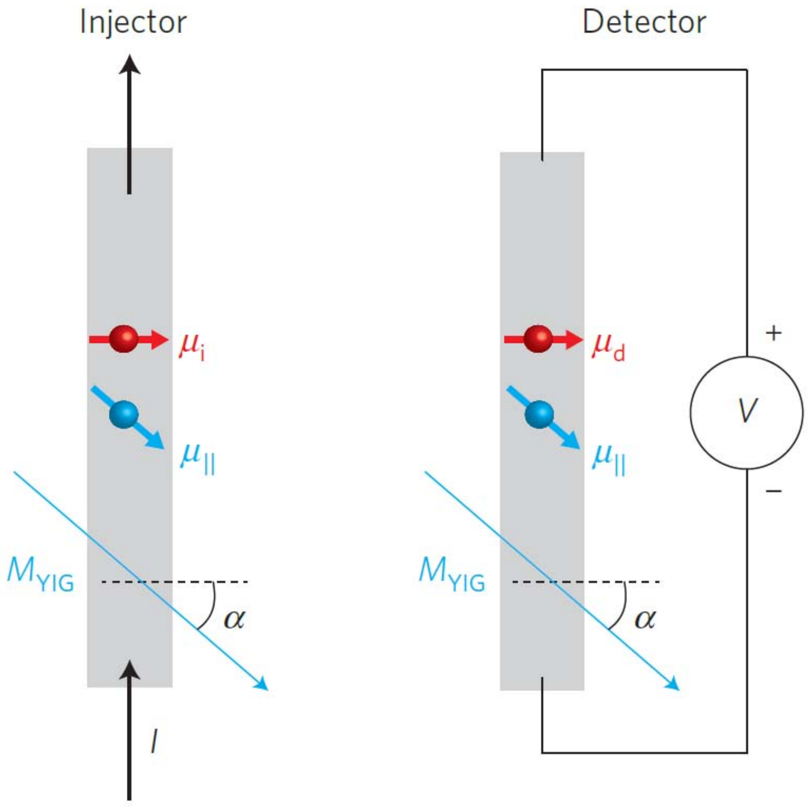
Magnon spintronics: electical control over magnon spin currents

Magnonic many-body physics

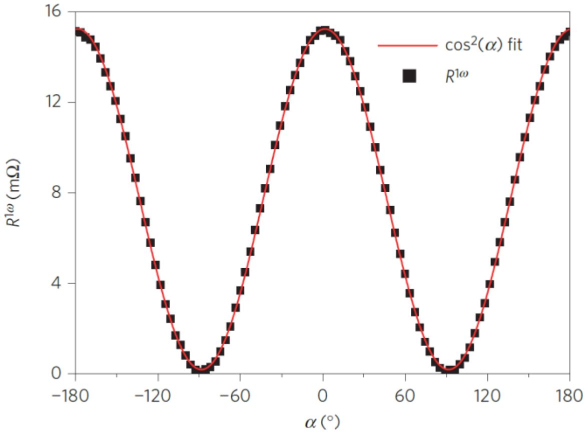
Route to spin currents with low dissipation

Interfacial spin current



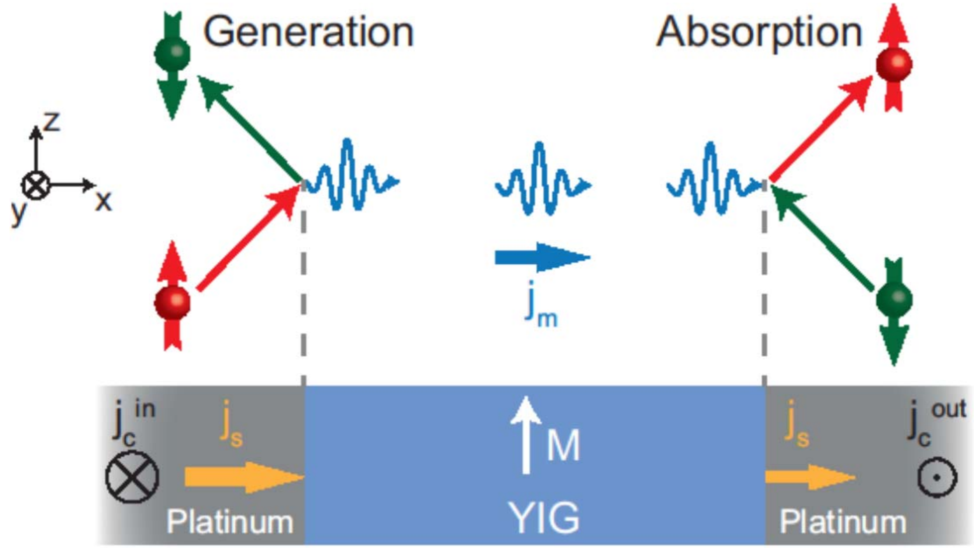


R=V/I



$$\cos^2\alpha = \cos\alpha \quad * \quad \cos\alpha$$

Model



magnon diffusion & relaxation:

$$\vec{j}_s = -\sigma_m \nabla \mu$$

$$\nabla^2 \mu = \frac{\mu}{\ell_m^2}$$

signal ~ e^{-L/ℓ_m}

For spin superfluid this would be ~ $\dfrac{1}{1+CL}$

Takei and Tserkovnyak (2014); Flebus, Bender, Tserkovnyak, RD (2016)

QUANTUM SPINTRONICS

SPIN TRANSPORT THROUGH QUANTUM MAGNETIC MATERIALS

Workshop September 21st - 23rd 2016
JGU MITP/SPICE, Mainz, Germany

ORGANIZERS:
Rembert Duine
Yaroslav Tserkovnyak

SPICE CO-ORGANISER:
Jairo Sinova

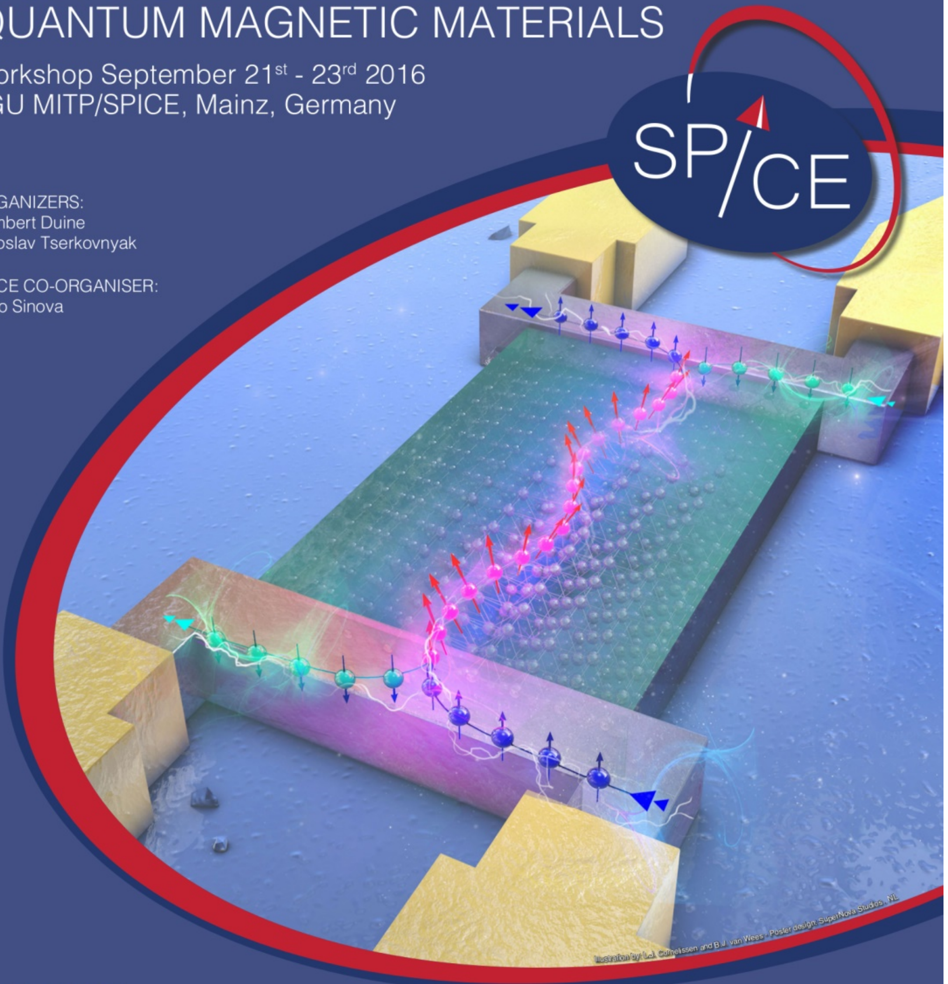


Illustration by: L.J. Cornelissen and B.J. van Wees - Poster design: SuperNova Studios , NL

INVITED SPEAKERS:

Leon Balents (KITP)
Arne Brataas (NTNU)
Hans-Benjamin Braun (Dublin)
David G. Cahill (UIUC)
Ludo J. Cornelissen (Groningen)
Benedetta Flebus (Utrecht)
Thierry Giamarchi (Geneve)
Sebastian Goennenwein (Munich)

Fabian Heidrich-Meissner (Munich)
Peter Kopietz (Frankfurt)
Ilya Krivorotov (UC Irvine)
Daniel Loss (Basel)
Allan MacDonald (UT Austin)
Tamara Nunner (Berlin)
Teruo Ono (Kyoto)
Christian Rüegg (PSI)

Subir Sachdev (Harvard)
Eiji Saitoh (Sendai)
Dirk Schuricht (Utrecht)
Alexander Serga (Kaiserslautern)
So Takei (New York)
Wolfgang Wernsdorfer (Néel)
Amir Yacoby (Harvard)

The Spin Phenomena Interdisciplinary Center aims to bring together scientists from diverse disciplines and of varying seniority in the broad area of spin related research. Its goal is to break down scientific barriers and foster emergent areas of research that combine the strengths of different fields.

WWW.SPICE.UNI-MAINZ.DE

Take home messages

- Spin superfluidity is not ferromagnetic superfluidity

- Spinor Bose gas can be spin and/or mass superfluid

- Recent developments of spintronics pave the way for integration electronic and magnonic (eventually superfluid) low-dissipation spin currents & bosonic many-body physics