Spin current in all its guises

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Department of Applied Physics, Eindhoven University of Technology
QuSpin, NTNU

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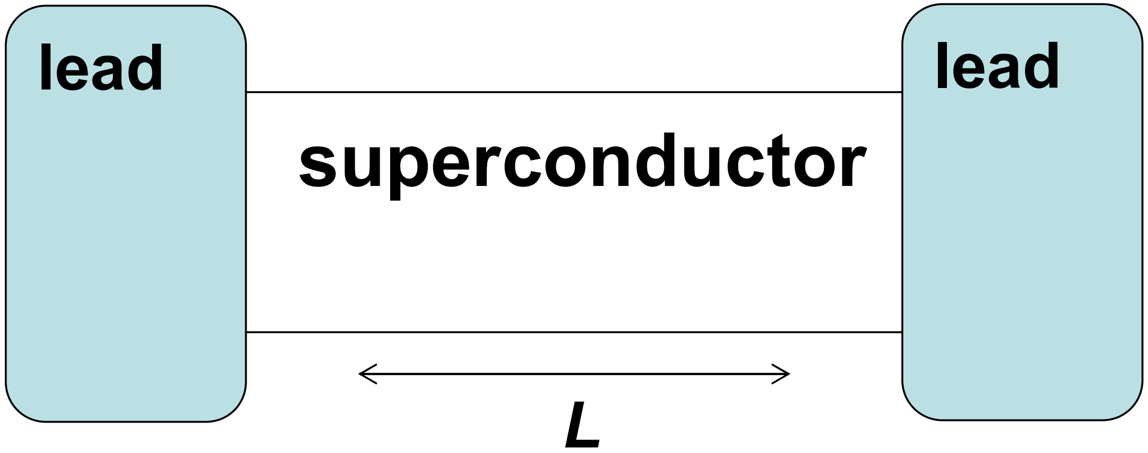
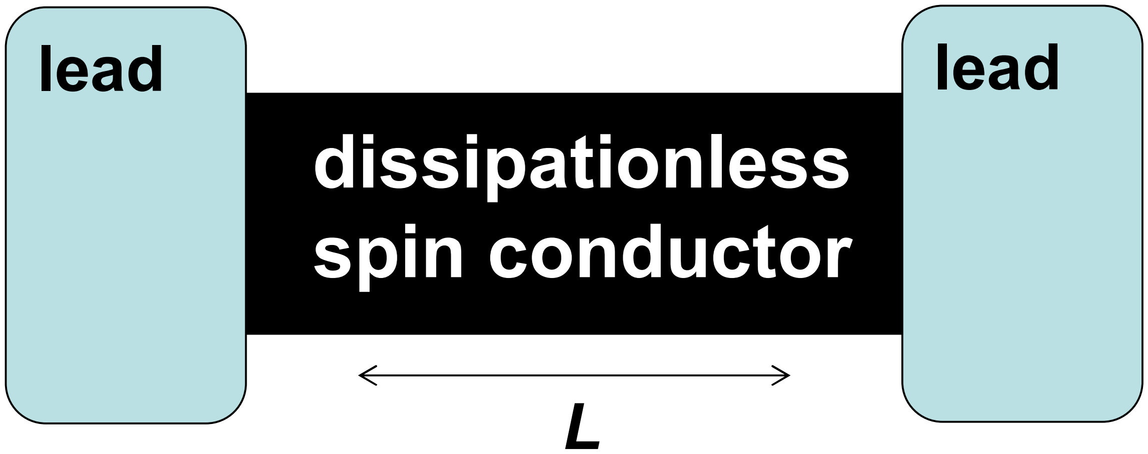
QuSpin

Long-term motivation



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

below room *T*



?

above room *T?*

What is spin?

What is spin?

What is spin?

Hans C. Ohanian
Rensselaer Polytechnic Institute, Troy, New York 12180

(Received 5 February 1984; accepted for publication 1 May 1985)

"The spin angular momentum is given by the part of the angular momentum that is independent of the origin of the coordinate system."

Potential issue: real vs. pseudo angular momentum

Ohanian, Am. J. Phys. (1986); Simon Streib, arXiv:2010.15616 (2020)

Outline

- General considerations
- Electronic spin transport
- Electrically controlled spin transport through electrically-insulating magnets
- Phonon spin transport through insulators

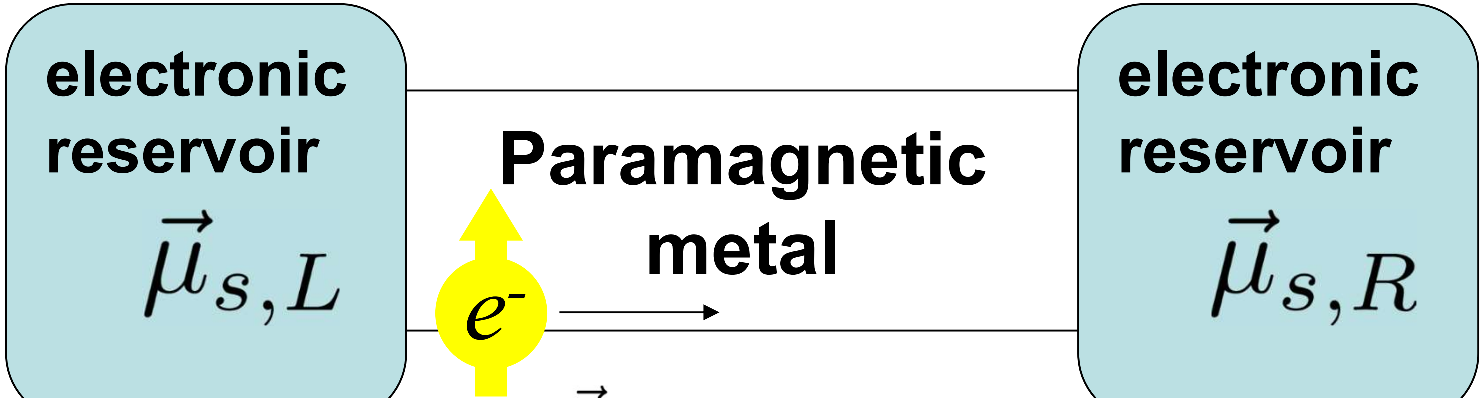
Spin transport in a world where spin is conserved

Spin accumulation: $\vec{\mu}_{s,L/R} = \dfrac{\partial F}{\partial \vec{S}_{L/R}}$

$$\frac{\partial \vec{S}}{\partial t} = -\boldsymbol{\nabla} \cdot \vec{\mathbf{j}}_s$$

spin current

Spin transport in a world where spin is conserved: electronic diffusive spin transport

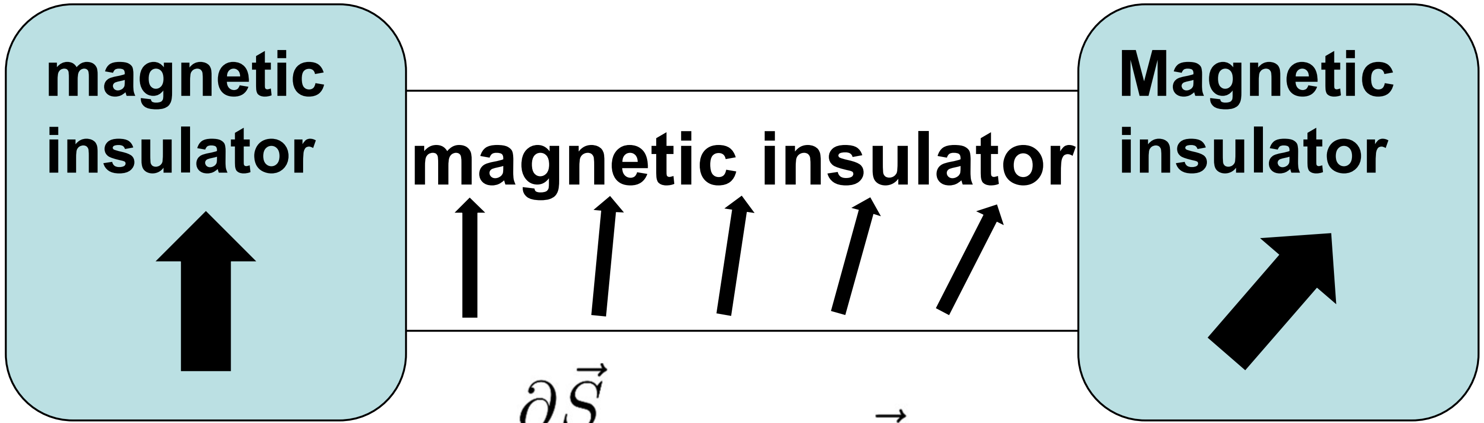


$$\frac{\partial \vec{S}}{\partial t} = -\nabla \cdot \vec{\mathbf{j}}_s$$

$$\vec{\mathbf{j}}_s = -D_s \nabla \vec{S} \sim -\sigma_s \nabla \vec{\mu}_s$$

+ boundary conditions, e.g.: $\vec{I}_{s,int} = G_s \left(\vec{\mu}_{s,L} - \vec{\mu}_{s,int} \right)$

Spin transport in a world where spin is conserved: exchange spin currents



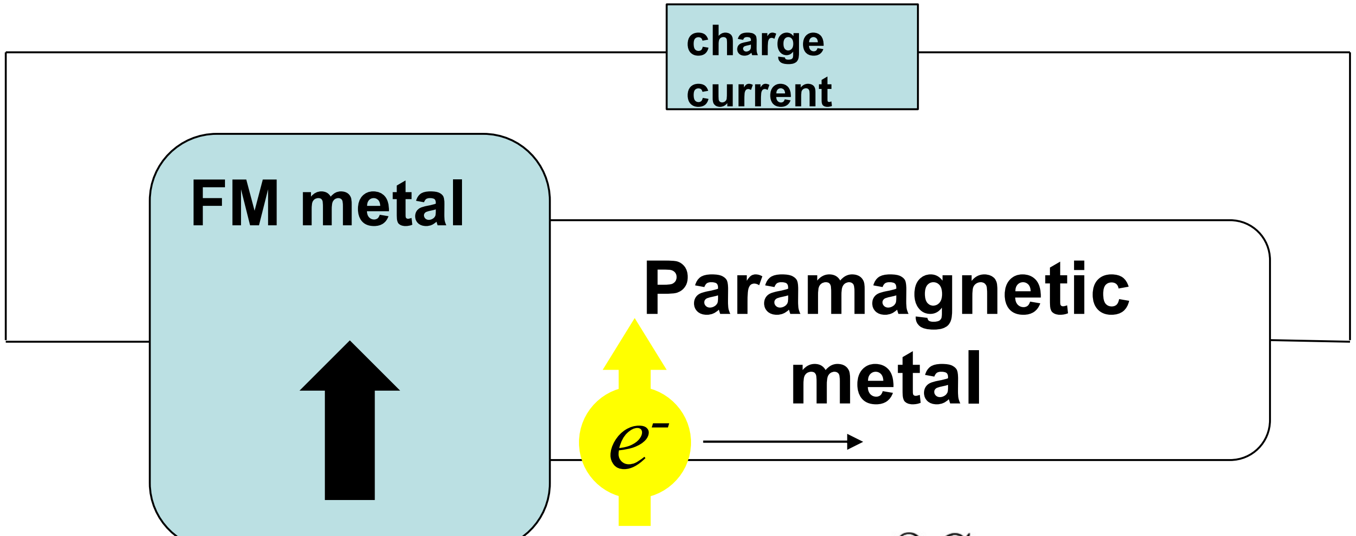
$$\frac{\partial \vec{S}}{\partial t} = -\boldsymbol{\nabla} \cdot \vec{\mathbf{j}}_s$$

$$\vec{\mathbf{j}}_s \sim J_s \vec{S} \times \boldsymbol{\nabla} \vec{S}$$

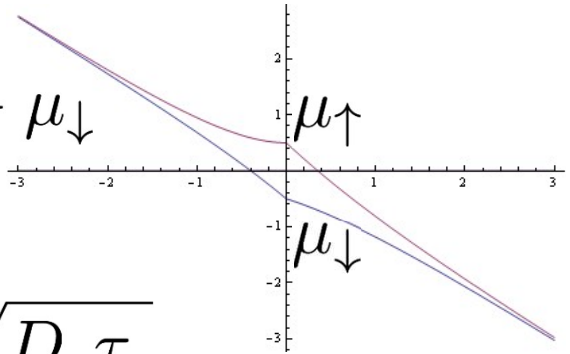
+ interface exchange coupling

For more discussion: see Rueckriegel & Kopietz (2017)

Spin transport in the real world: diffusive electrons



$$\mu_s = \mu_\uparrow - \mu_\downarrow$$



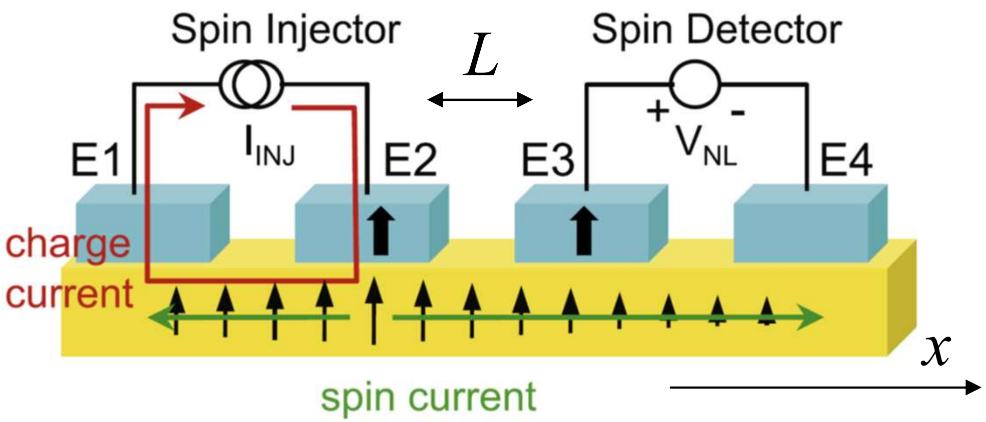
$$\ell_s = \sqrt{D_s \tau_s}$$

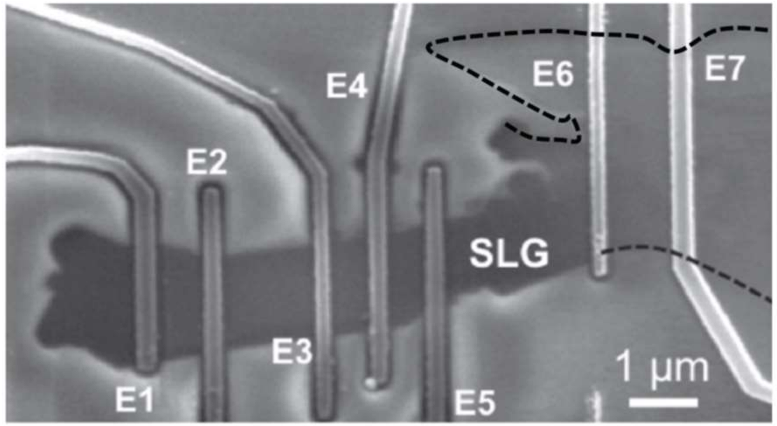
$$\frac{\partial S}{\partial t} = -\nabla \cdot \mathbf{j}_s - \frac{S}{\tau_s}$$

$$\mathbf{j}_s = -D_s \nabla S \sim -\sigma_s \nabla \mu_s$$

+ eqs. for charge transport
& boundary conditions

Non-local spin transport in metals/semi-conductors





graphene device

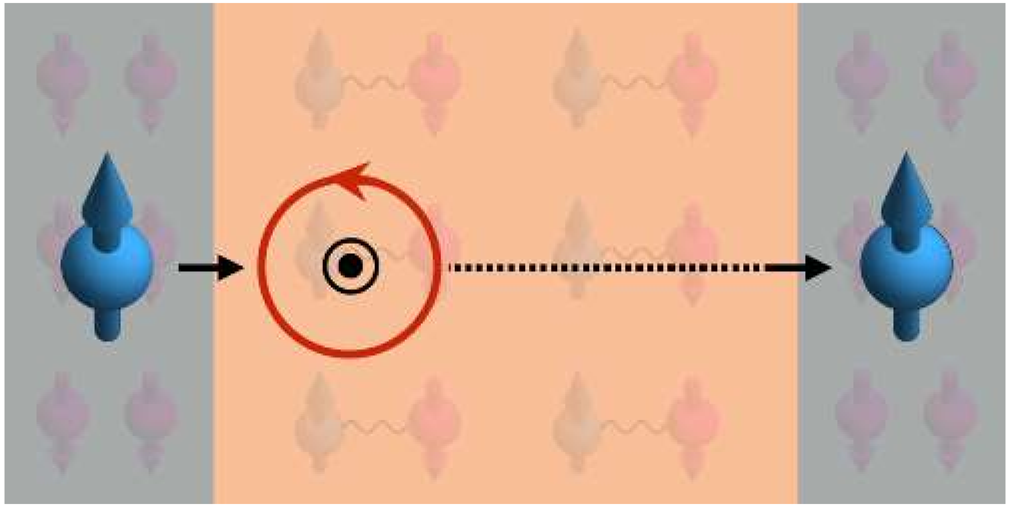
electron spin accumulation: $\mu_s \propto e^{-x/\ell_s}$

non-local resistance: $R_{\rm NL} \sim \dfrac{V_{\rm NL}}{I_{\rm INJ}} \propto e^{-L/\ell_s}$

spin-diffusion length: $\ell_s \sim {\rm nm} - \mu{\rm m}$

From Wei Han et al., JMMM ***324****, 369 (2012)*

More exotic forms of electronic spin transport: using vorticity



picture from physics.aps.org

Superconductors: *Kim, Myers & Tserkovnyak (2018)*
Viscous electron systems: *Doornenbal, Polini & Duine (2019); Matsuo, et al. arXiv:2005.01493*

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- **Phonon spin transport through insulators**

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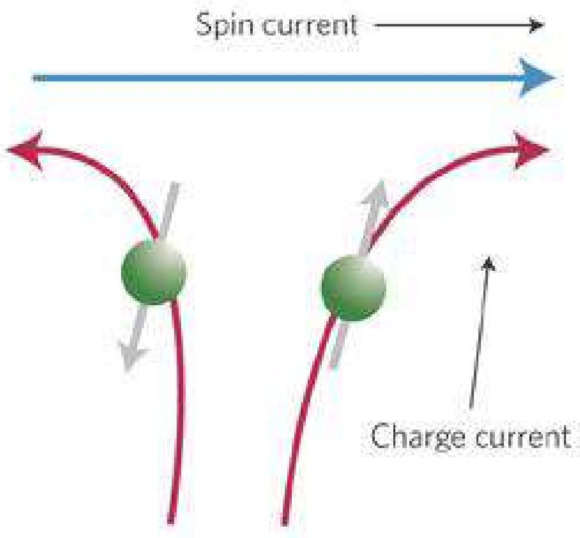
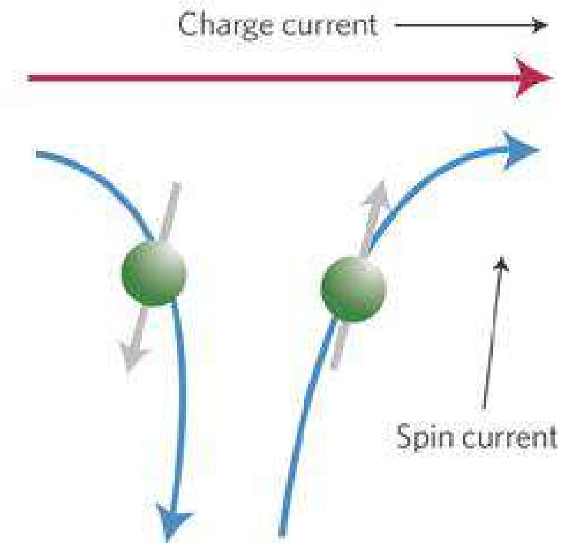
How to inject an electronic spin current into an insulator?

(Inverse) spin Hall effect

injection of spin current



detection of spin current



- **Microscopic mechanism: spin-orbit coupling**
- **Material: Pt**
- **Spin Hall effect establishes spin accumulation μ_s**

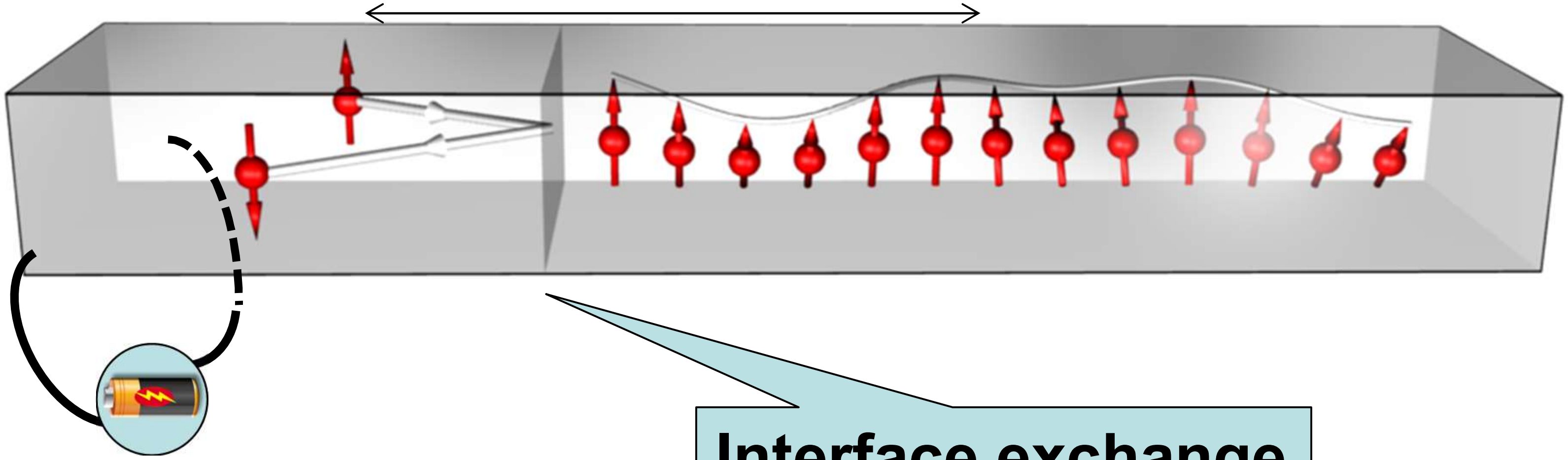
Nature Materials ***8****, 777 (2009)*

Injection (+detection) of spin current into a magnetic insulator

paramagnetic metal (NM) with large spin Hall effect (Pt)

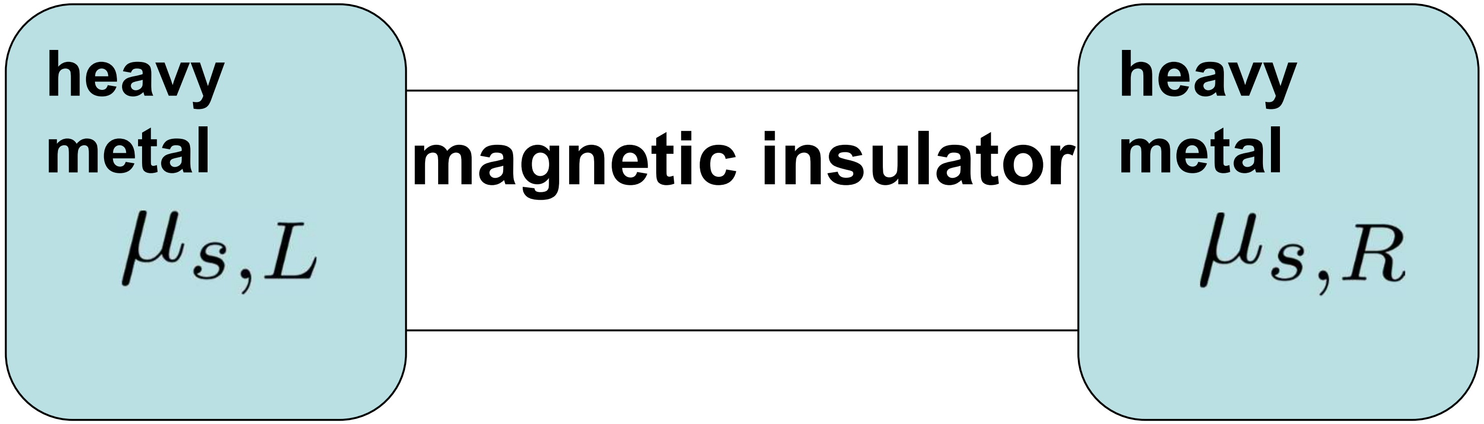
magnetic insulator

Spin and heat but no charge flow



Interface exchange coupling

Spin transport through insulators

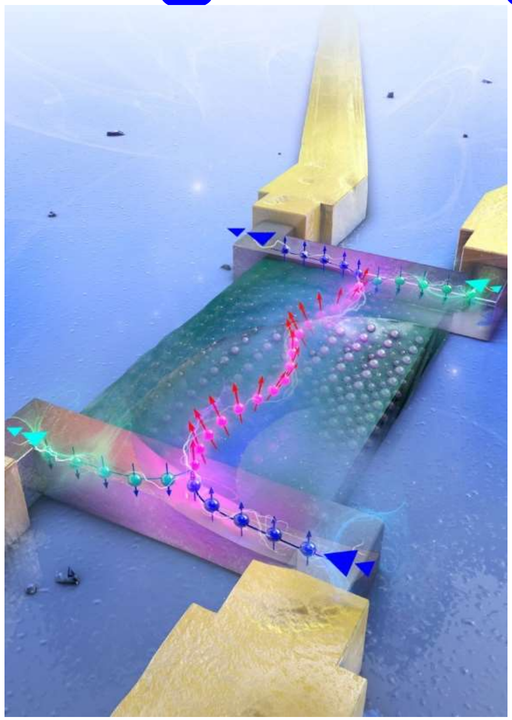


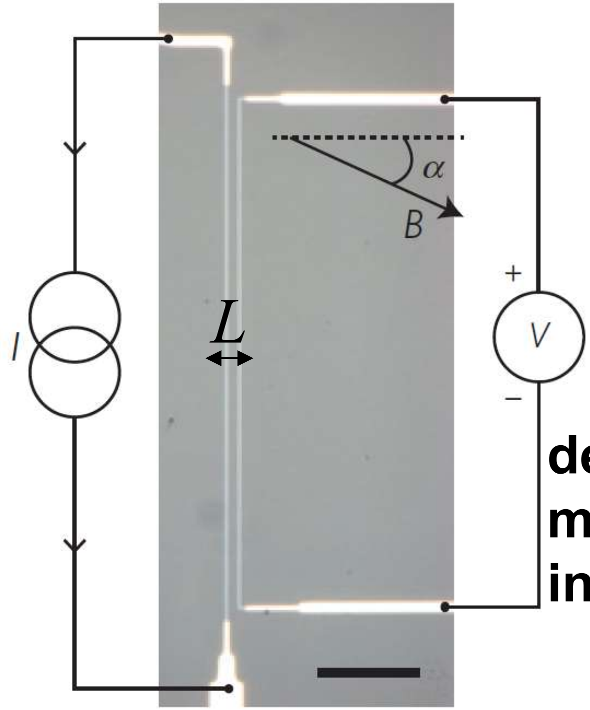
$$\frac{\partial S}{\partial t} = -\boldsymbol{\nabla} \cdot \mathbf{j}_s$$

+ spin relaxation + boundary conditions

Cornelissen, ..., RD, et al., Nature Physics **11**, 1022 (2015); for AFMs: Lebrun, ..., RD, et al., Nature 561, 222 (2018)

Non-local spin transport through magnetic insulators





device: Pt on magnetic insulator YIG

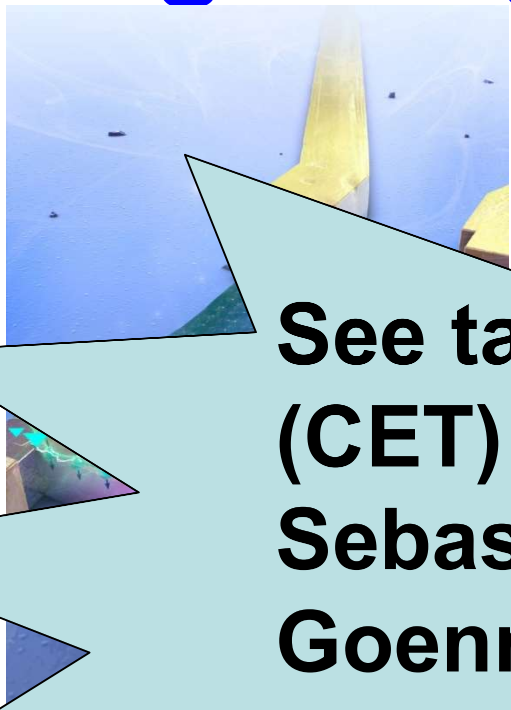
magnon spin accumulation: $\mu_m \propto e^{-x/\ell_m}$

non-local resistance: $R_{\rm NL} \sim V/I \propto e^{-L/\ell_m}$

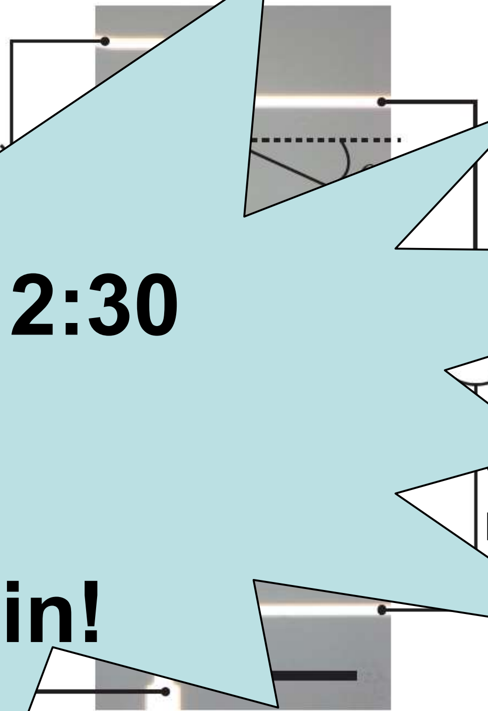
magnon spin diffusion length: $\ell_m \sim 10\ \mu{\rm m}$ **YIG @ room T**

Cornelissen, ..., RD, et al., Nature Physics **11**, 1022 (2015); for AFMs: Lebrun, ..., RD, et al., Nature 561, 222 (2018)

Non-local spin transport through magnetic insulators



See talk at 12:30 (CET) by Sebastian Goennenwein!



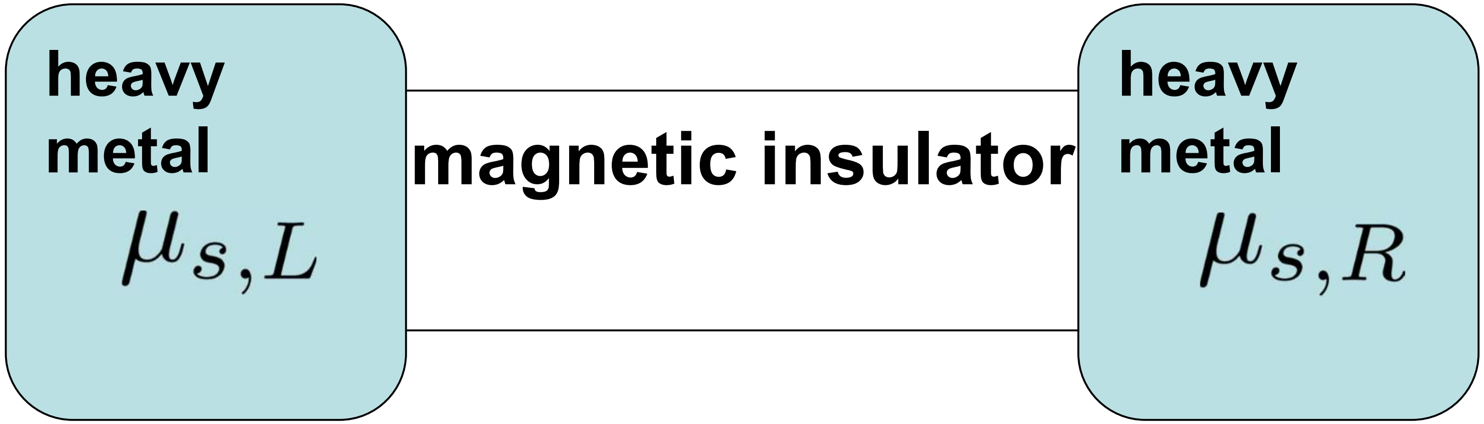
...evice: Pt on magnetic ...sulator YIG

magnon spin accu... ...on: $\propto e^{-\ldots/\ell_m}$

non-local resistance: $R_{\mathrm{NL}} \sim V/I \propto e^{-L/\ell_m}$

magnon spin diffusion length: $\ell_m \sim 10\ \mu\mathrm{m}$ **YIG @ room T**

Spin transport through insulators: diffusive magnons

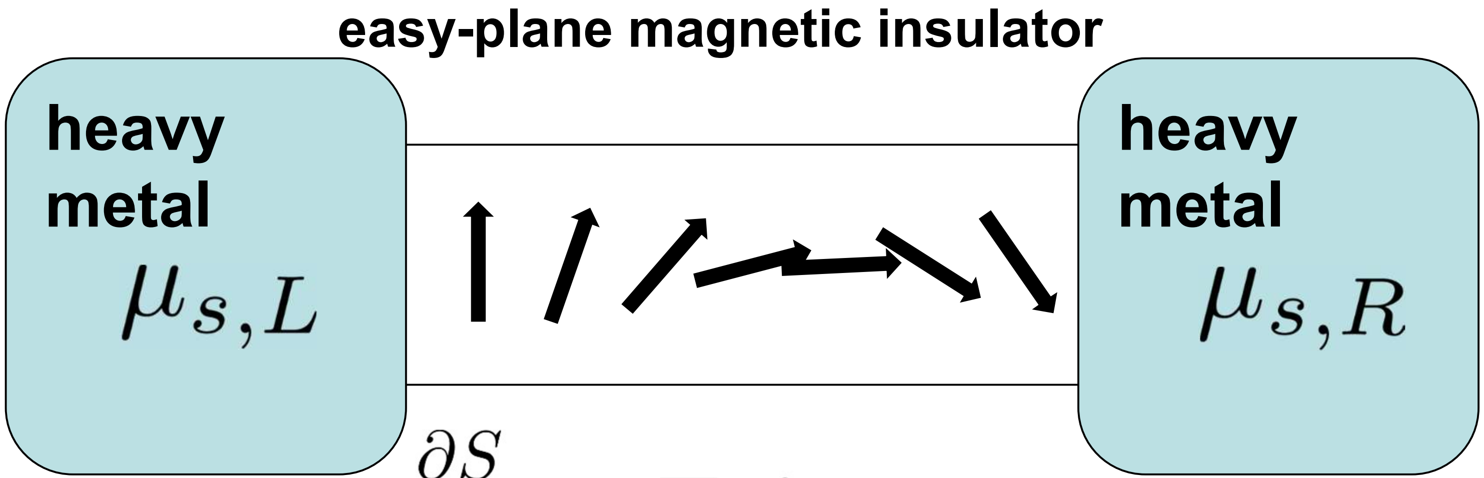


$$\frac{\partial S}{\partial t} = -\boldsymbol{\nabla} \cdot \mathbf{j}_s - \frac{S}{\tau_m} \qquad \ell_m = \sqrt{D_m \tau_m}$$

$$\mathbf{j}_m = -D_m \boldsymbol{\nabla} S \sim -\sigma_m \boldsymbol{\nabla} \mu_m$$

+ boundary conditions

Spin transport through insulators: spin superfluidity



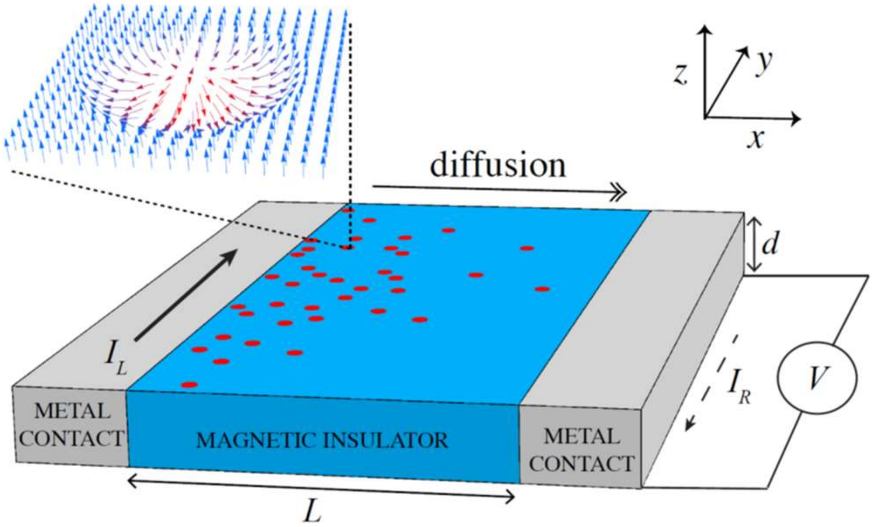
$$\frac{\partial S}{\partial t} = -\boldsymbol{\nabla} \cdot \mathbf{j}_s$$

$$\mathbf{j}_s \sim J_s \, \vec{S} \times \boldsymbol{\nabla} \vec{S} \Big|_z \sim \nabla \phi$$

+ boundary conditions + spin-non-conserving effects (lead to algebraic decay & lower critical current)

Sonin (2010); for He-3: Bunkov et al.; Takei & Tserkovnyak (2014); Flebus, Bender, Tserkovnyak & Duine (2016)

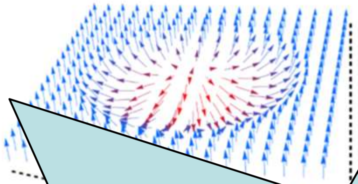
More "exotic" forms of (spin) transport through insulators



- **Topological transport (Tserkovnyak, Kim, Ochoa, …see picture)**
- **Quantum spin liquids**
- **Spinons & paramagnetic GGG (Saitoh group)**
- **Antiferromagnets (Klaui, Wei Han, …)**
- **Van der Waals magnets (Wei Han, …)**
- **…**

Review: Wei Han, et al., Nature Materials (2020)

More “exotic” forms of (spin) transport through insulators



Talk by So Takei at 12 am (CET)!

- **Top… , Kim, Ochoa, …see picture)**
- **Quantum spi… ids**
- **Spinons & paramagnetic GGG (Saitoh group)**
- **Antiferromagnets (Klaui, Wei Han, …)**
- **Van der Waals magnets (Wei Han, …)**
- **…**

Review et al.: Wei Han, Nature Materials (2020)

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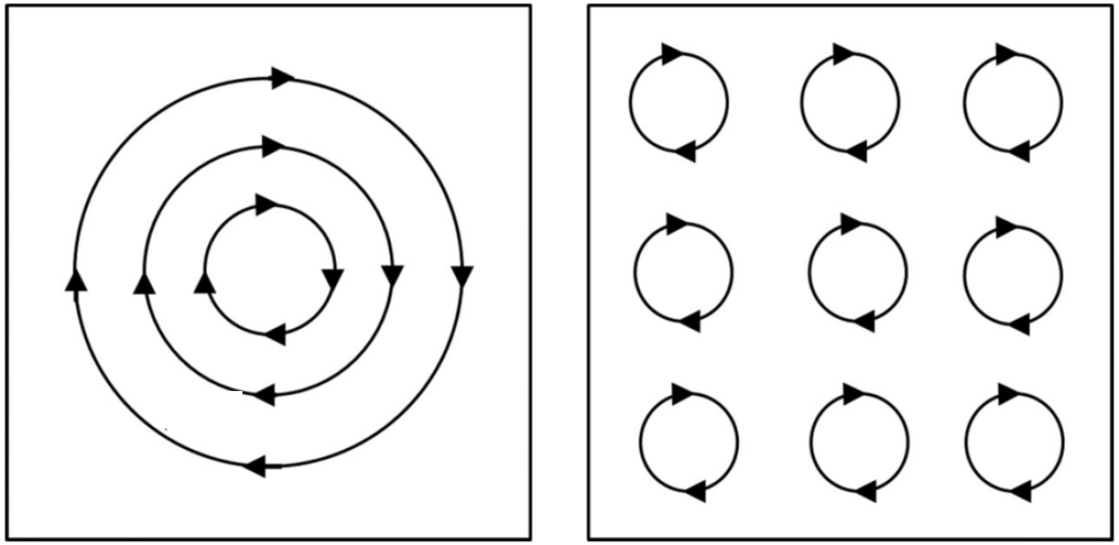
Circularly-polarized phonons carry spin angular momentum

PHONON SPIN

S. V. Vonsovskii and M. S Svirskii

Institute of Metal Physics, Academy of Sciences, USSR, Sverdlovsk;
Chelyabinsk Pedagogical Institute
Translated from Fizika Tverdogo Tela, Vol. 3, No. 7,
pp. 2160-2165, July, 1961
Original article submitted March 18, 1961

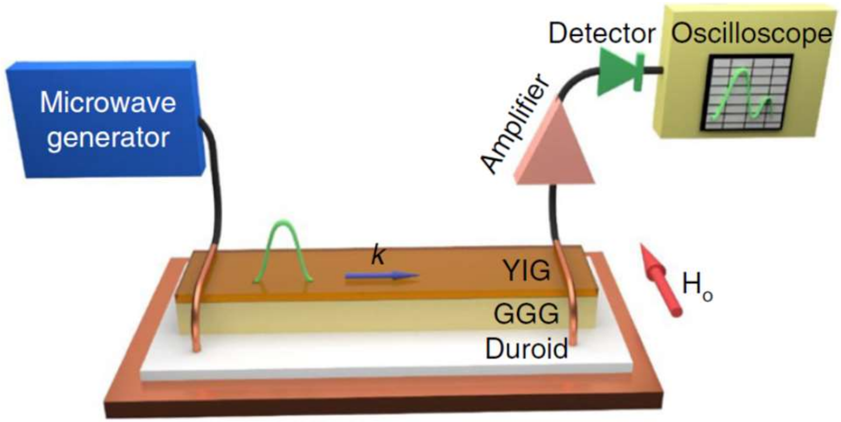


global rotation **phonon spin**

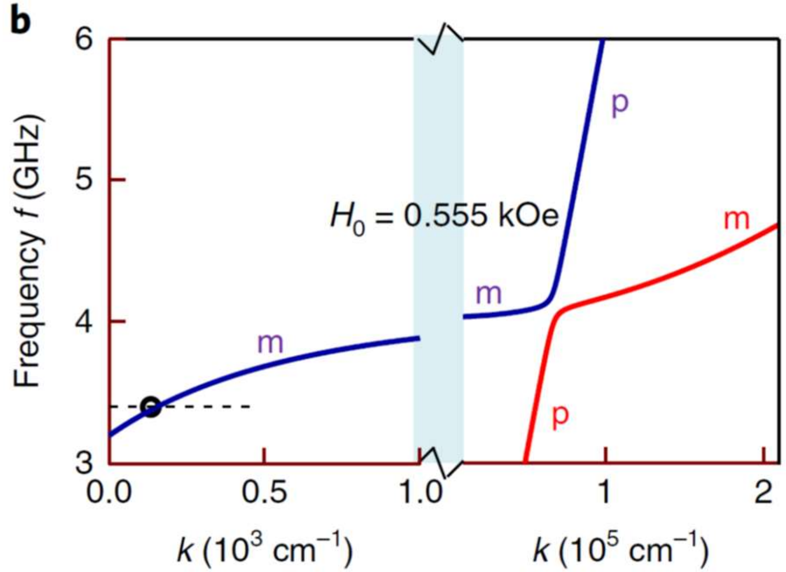
Vonsovskii, Svirskii (1962), Levine (1962); Zhang, Niu (2014); Picture above: Garanin, Chudnovsky (2015), Nakane, Kohno (2018), Streib, Keshtgar, Bauer (2018), Juraschek, Spaldin (2019).

Experimental detection phonon spin (I)

set-up:



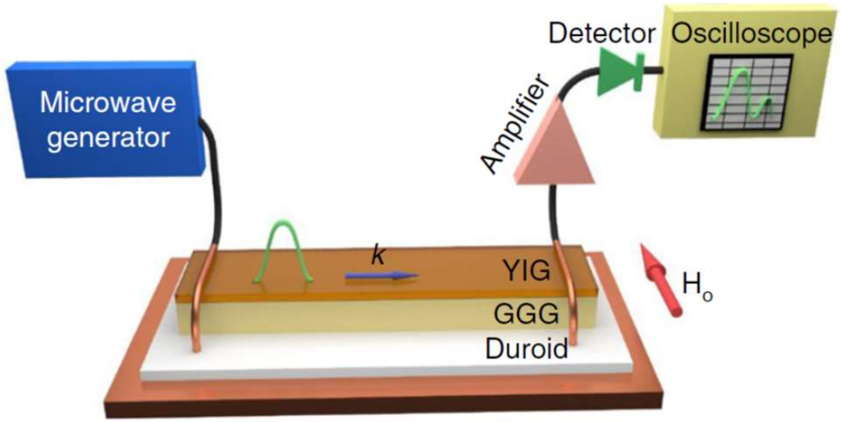
dispersion relation:



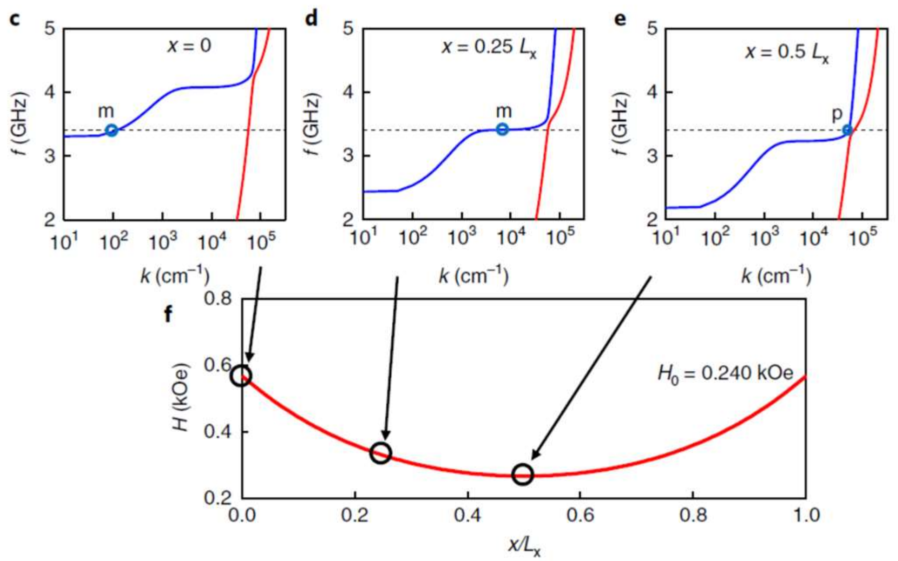
Holanda et al, Nat. Phys (2018)

Experimental detection phonon spin (II)

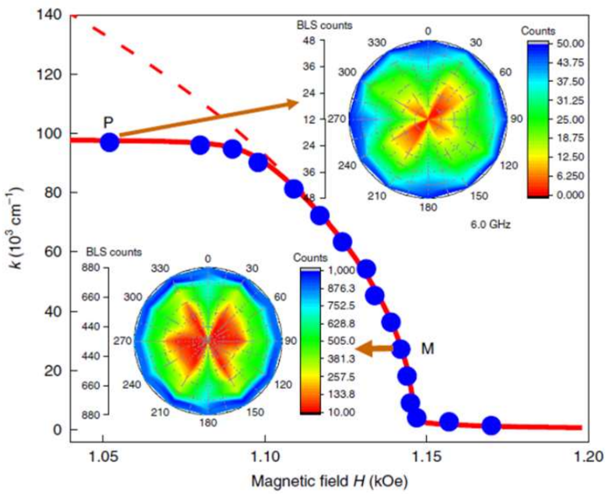
set-up:



magnon-phonon conversion:



result:

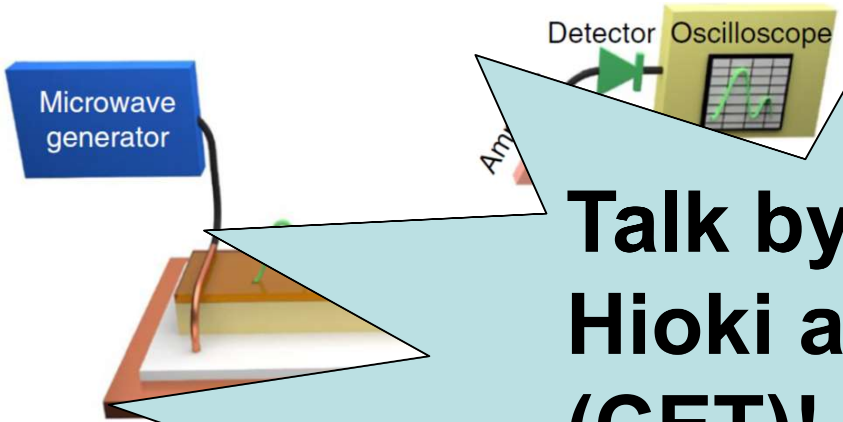


- Excitation of magnon (spin $\approx \hbar$)
- Conversion to phonon
- Measurement of phonon polarization

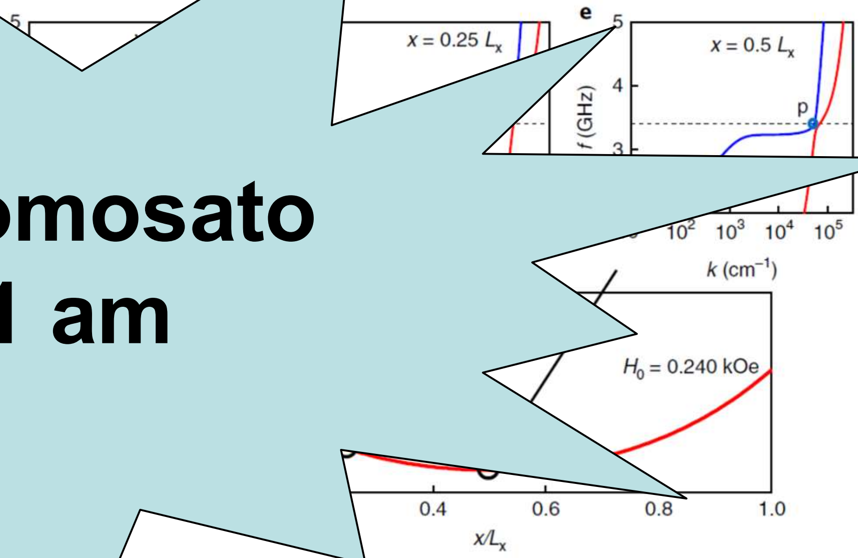
Holanda et al, Nat. Phys (2018)

Experimental detection phonon spin (II)

set-up:

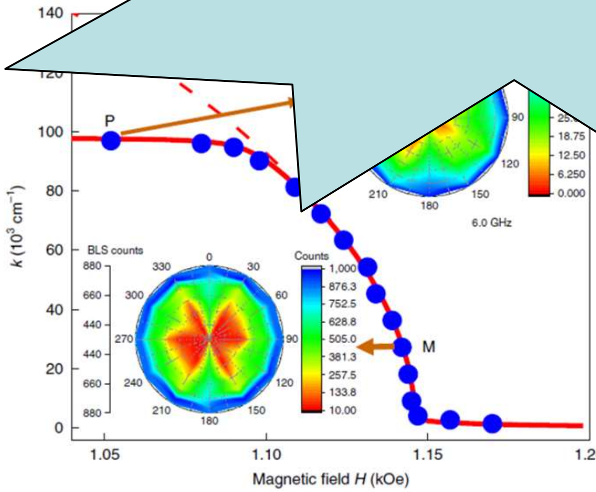


magnon-phonon conversion:



Talk by Tomosato Hioki at 11 am (CET)!

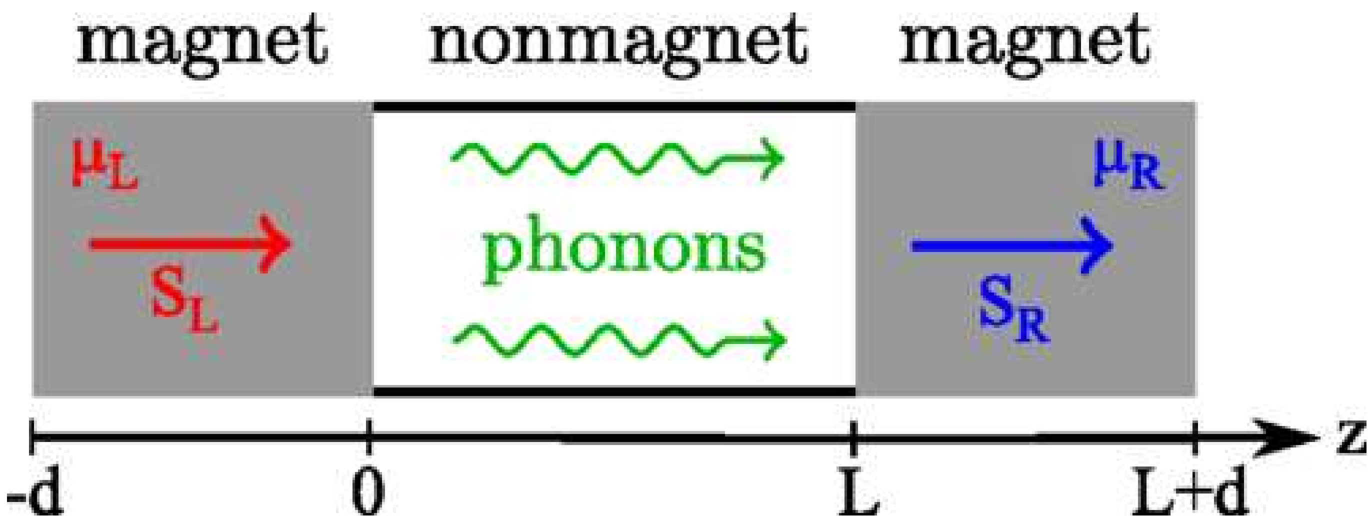
result:



- **Excitation of magnon (spin $\approx \hbar$)**
- **Conversion to phonon**
- **Measurement of phonon polarization**

Holanda et al, Nat. Phys (2018)

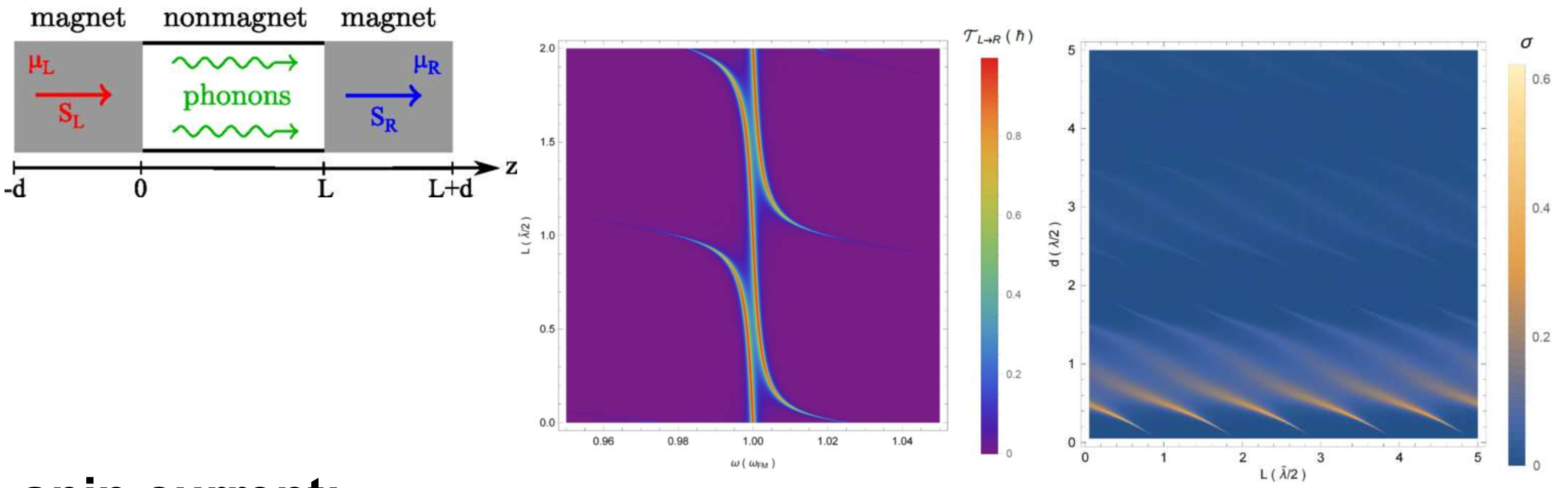
Set-up



- Incoherently driven magnetic reservoirs
- Non-magnetic insulator
- Spin transfer due to magnetoelastic interactions
- Theorical approach: coupled stochastic equations for magnetic and lattice dynamics

Phys. Rev. Lett. 124, 117201 (2020)

Spin-conductance & resonance condition



spin current:

$$I_{L\to R} = \int \frac{d\omega}{2\pi} T_{L\to R}(\omega)\left[f_B(\hbar\omega - \mu_L) - f_B(\hbar\omega - \mu_R)\right]$$

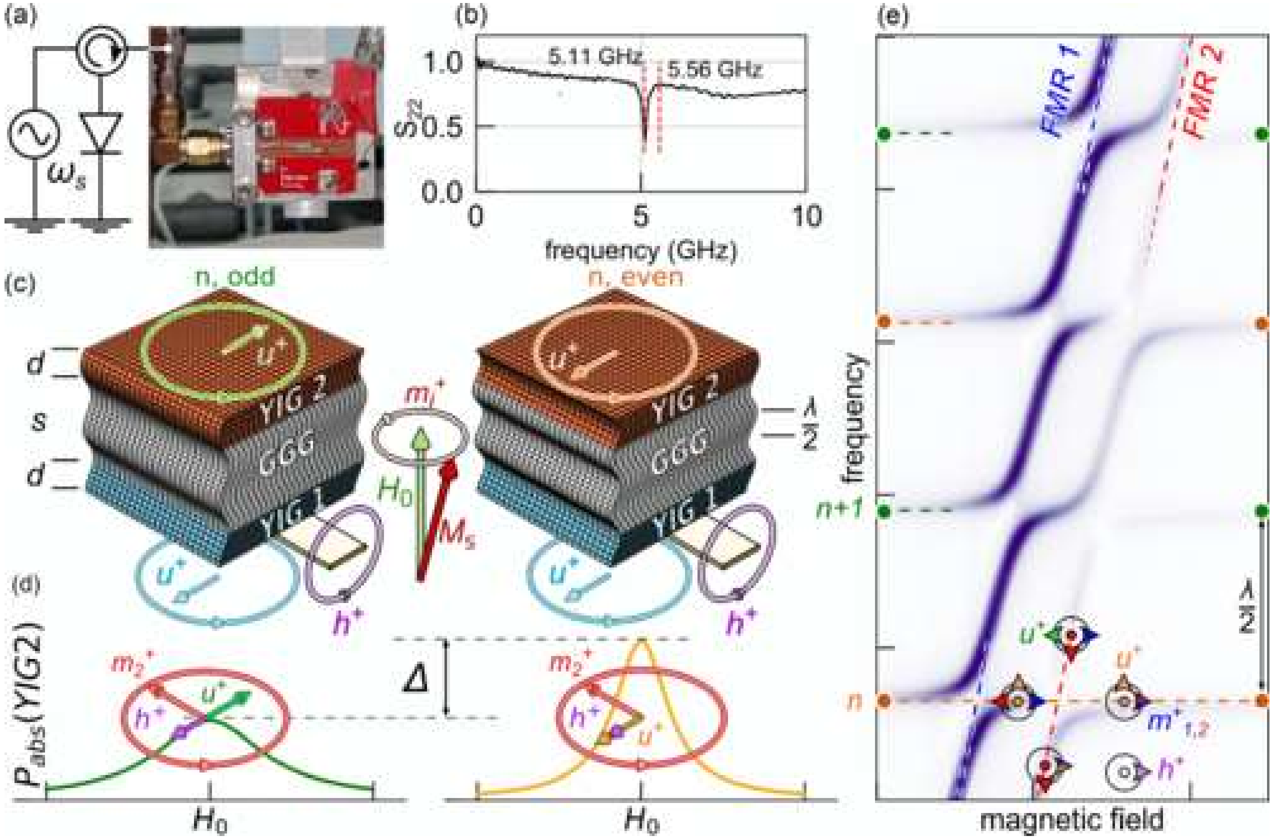
for small bias:

$$I_{L\to R} = \sigma(\mu_R - \mu_L)$$

resonance condition

$$L/(\tilde{\lambda}/2) + 2d/(\lambda/2) = \text{integer}$$

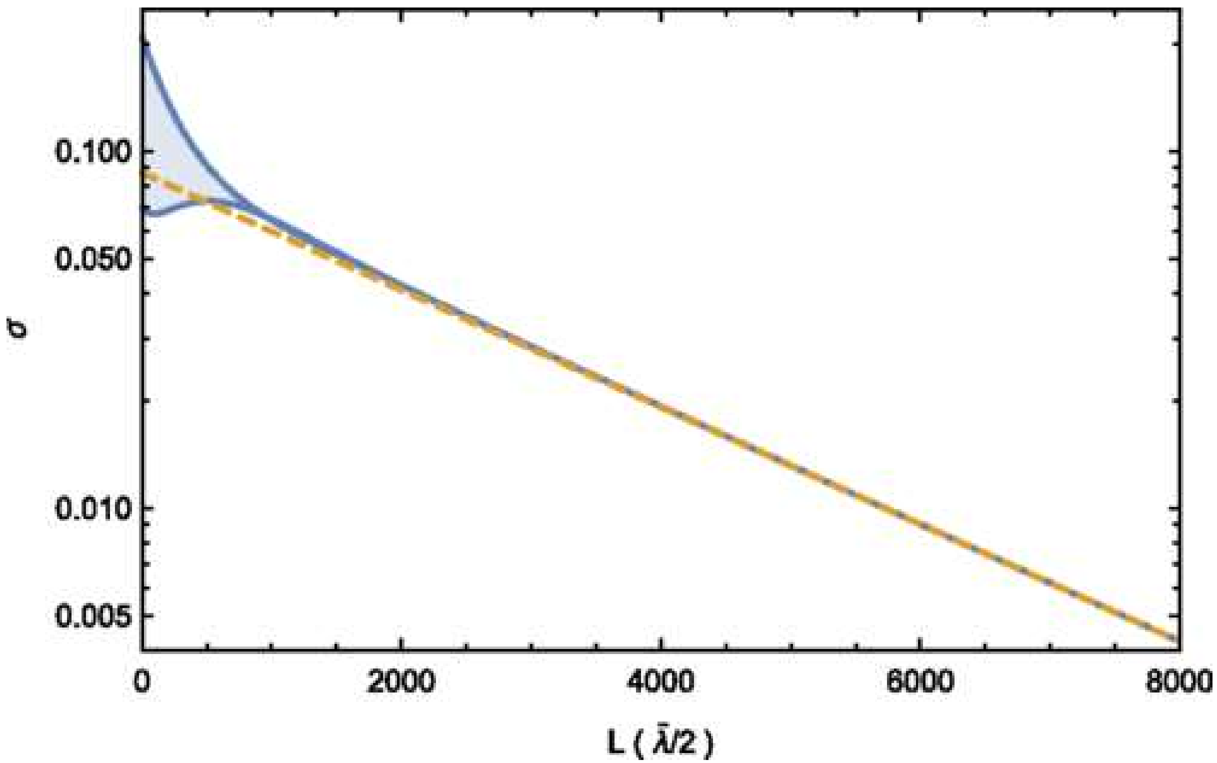
Experiments in coherent regime



FMR experiment, coherent coupling

An et al. Phys. Rev. B (2020), motivated by Streib et al. (2018)

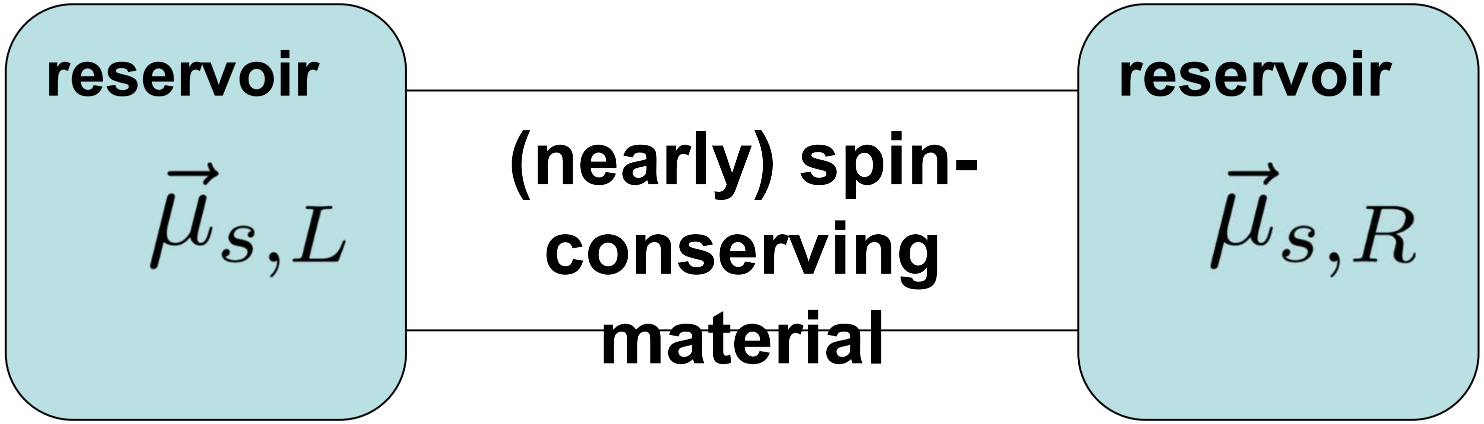
Long-range phonon spin currents



- YIG and GGG parameters
- Decay length ~ 1 mm

Take-home message

Take-home message



A lot of materials have been shown to be spin conductors, and many more will follow!
(And the record spin diffusion length is continuously broken.)