Long-Range Phonon Spin Transport

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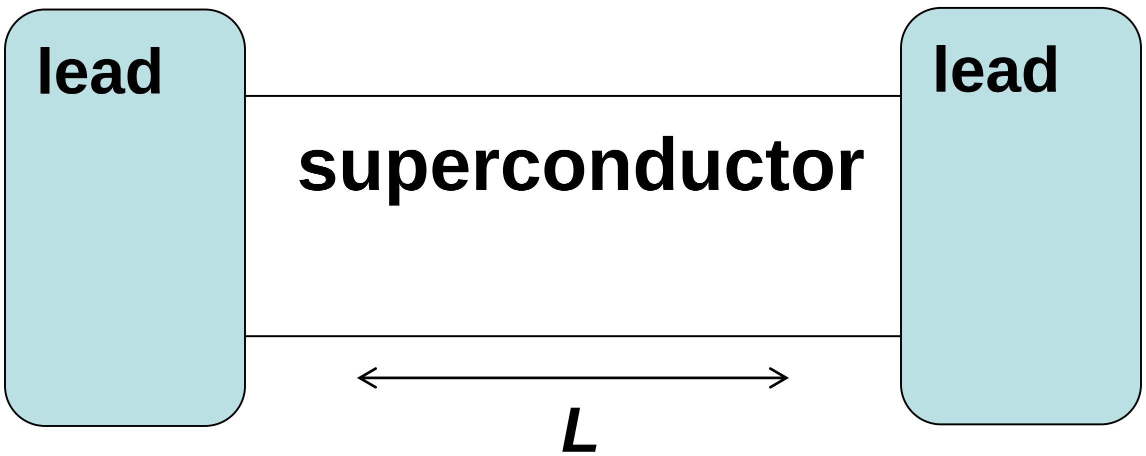
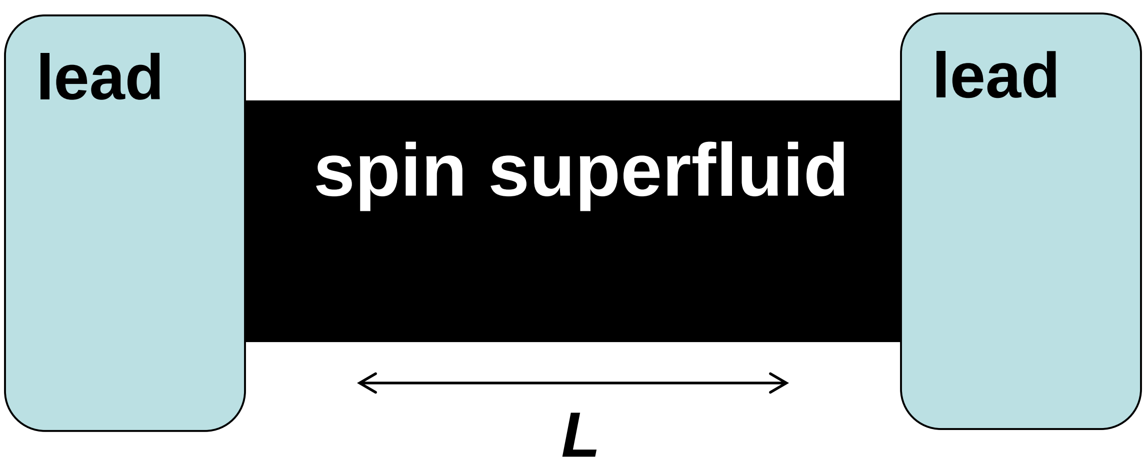
Phys. Rev. B 101, 104402 (2020); Phys. Rev. Lett. 124, 117201 (2020)

Long-term motivation



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

below room *T*

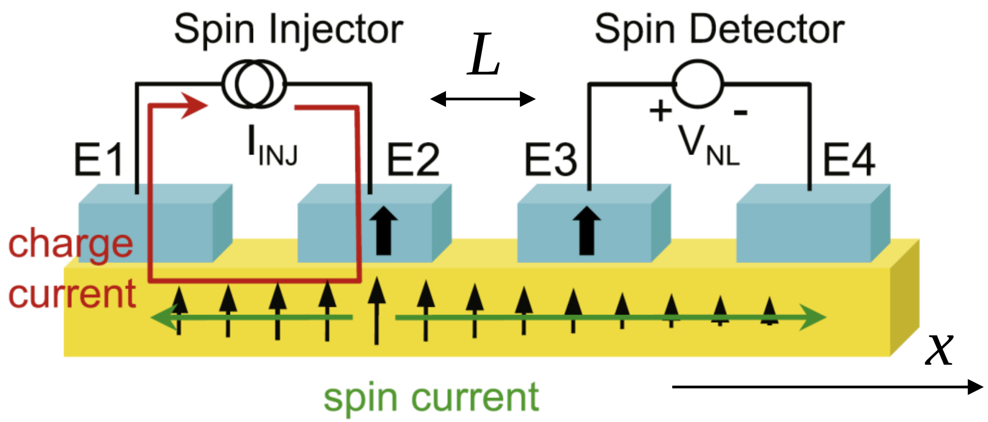


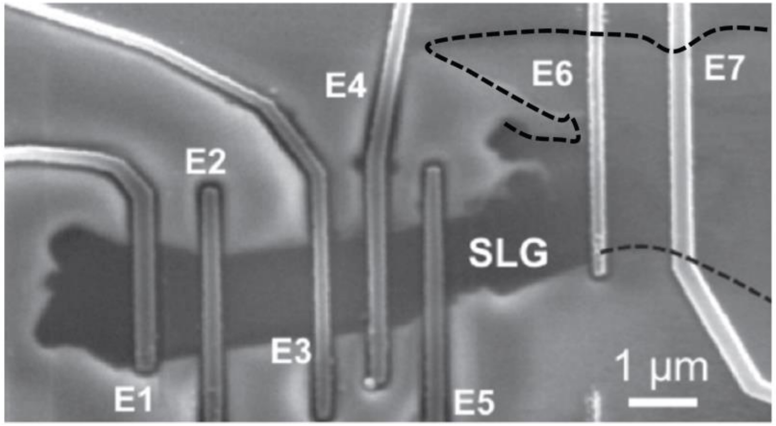
?

above room *T?*

See e.g. Sonin (2010)

Non-local spin transport in metals/semi-conductors





graphene device

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

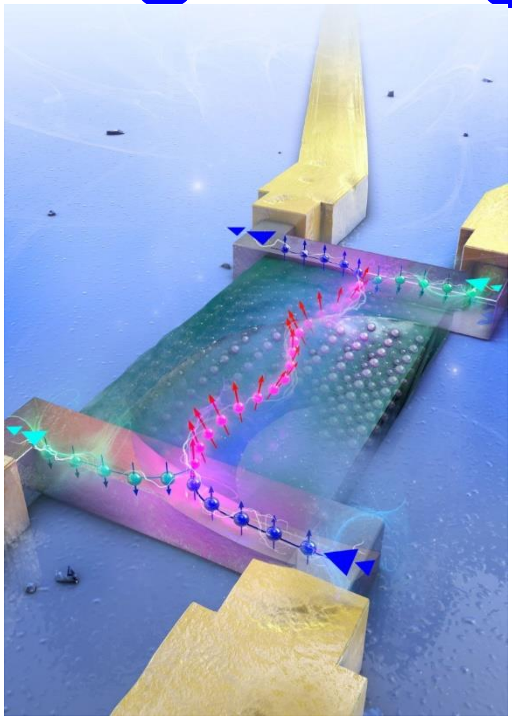
non-local resistance: $R_{\mathrm{NL}} \sim \dfrac{V_{\mathrm{NL}}}{I_{\mathrm{INJ}}} \propto e^{-L/\ell_s}$

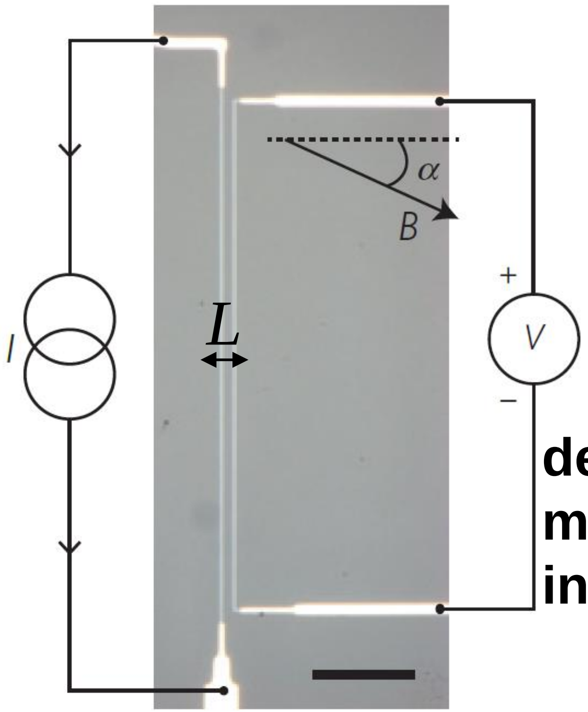
spin-diffusion length: $\ell_s \sim \mathrm{nm} - \mu\mathrm{m}$

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

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

Non-local spin transport though magnetic insulators





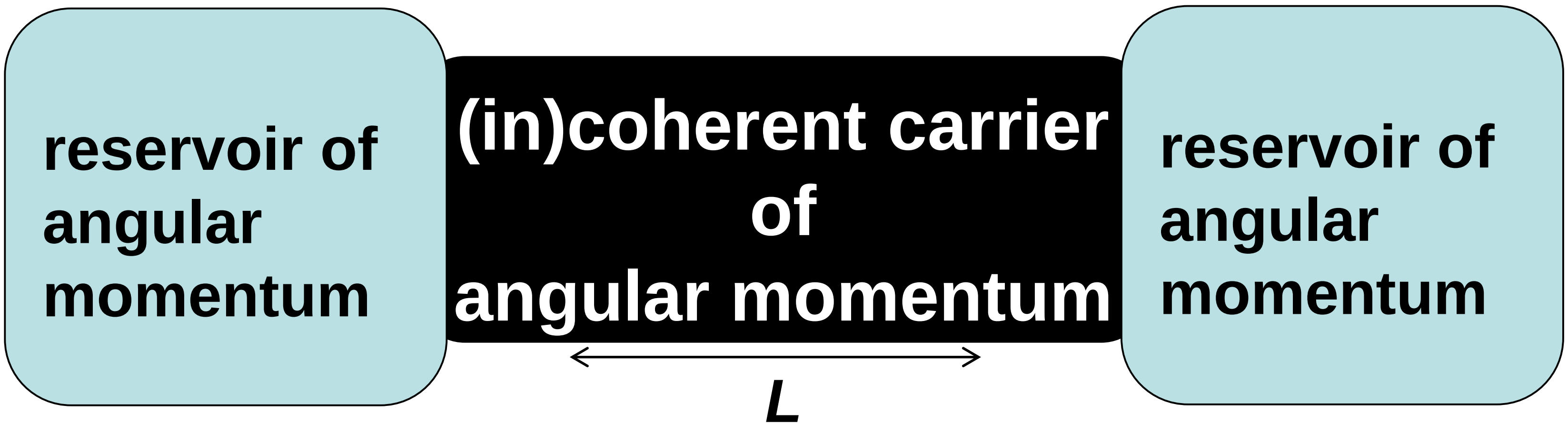
device: Pt on magnetic insulator YIG

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

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**

General view



- Electrons (100’s nm)
- Magnons (10’s μm)
- <u>This talk: phonons (mm’s)</u>

Collaborators

Andreas Rueckriegel (Utrecht -> Frankfurt)
Simon Streib (Uppsala)
Gerrit Bauer (Sendai, Groningen)

Andreas

Gerrit

Institute for Theoretical Physics

European Research Council

Outline

- **Phonon spin**

- **Role of phonons in Einstein-de Haas-like effects**

- **Long-range phonon spin currents**

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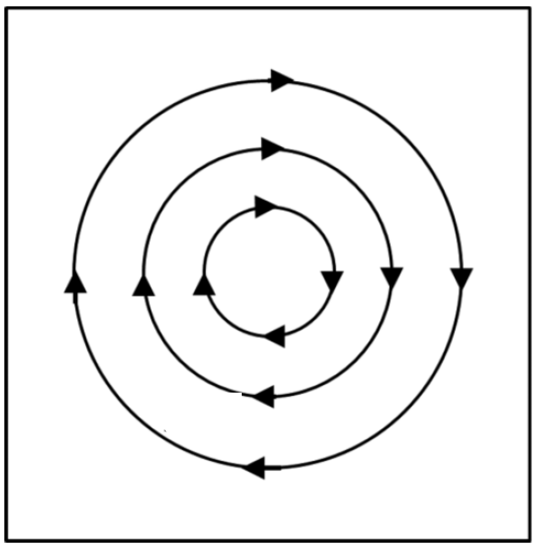
- **Phonon spin**
- **Role of phonons in Einstein-de Haas-like effects**
- **Long-range phonon spin currents**

Circularly-polarized phonons carry spin angular momentum

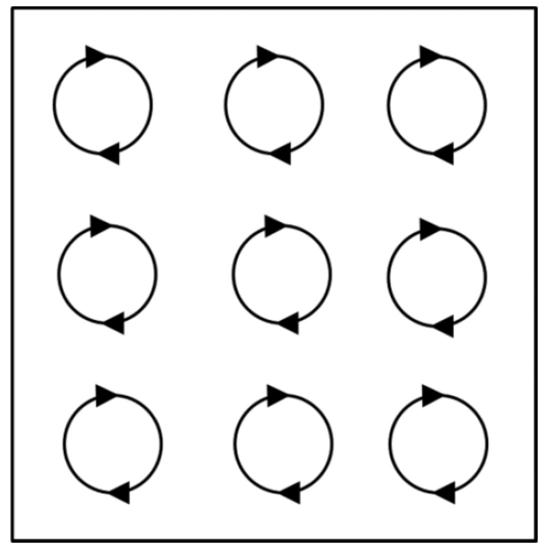
PHONON SPIN

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

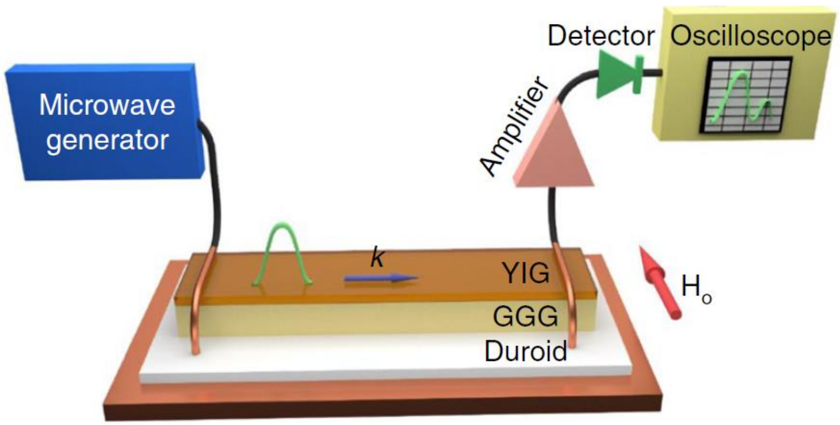


phonon spin

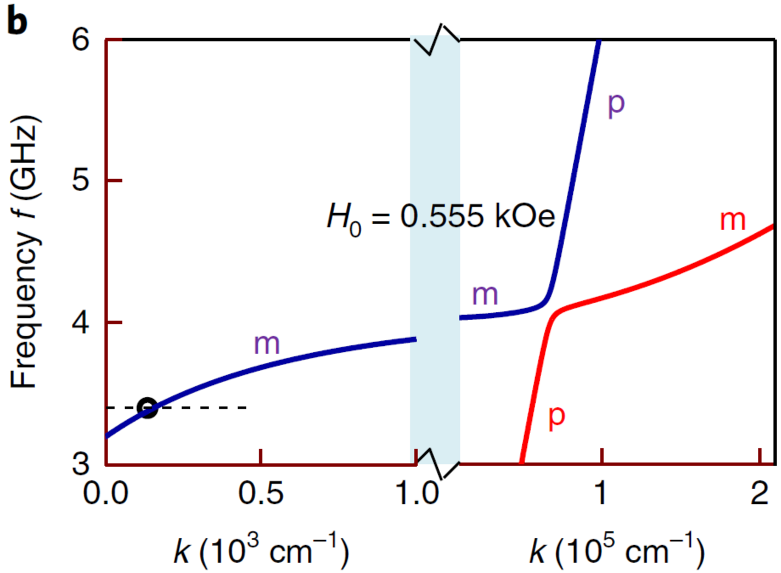
Vonsovskii, Svirskii (1962), Levine (1962); Zhang, Niu (2014); Picture above: Garanin, Chudnovsky (2015), Nakane, Kohno (2018), Streib, Keshtgar, Bauer (2018), Juraschek, Spaldin (2019).

Experimental detection phonon spin (I)

set-up:



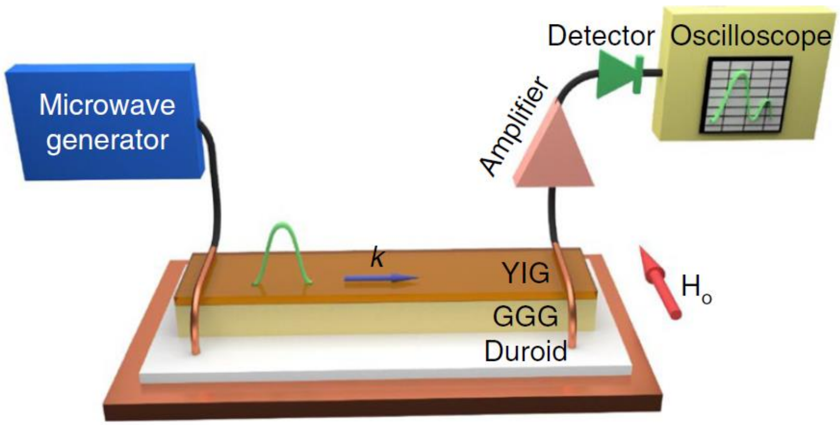
dispersion relation:



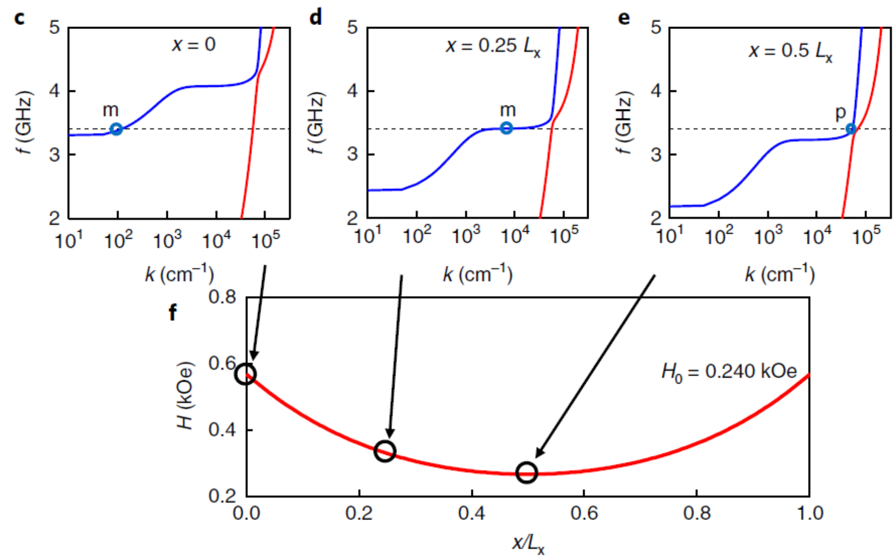
Holanda et al, Nat. Phys (2018)

Experimental detection phonon spin (II)

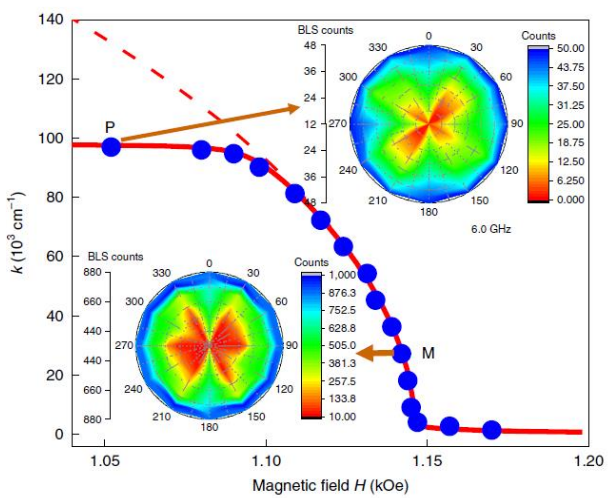
set-up:



magnon-phonon conversion:



result:



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

Holanda et al, Nat. Phys (2018)

Outline

- **Phonon spin**

- **Role of phonons in Einstein-de Haas-like effects**

- **Long-range phonon spin currents**

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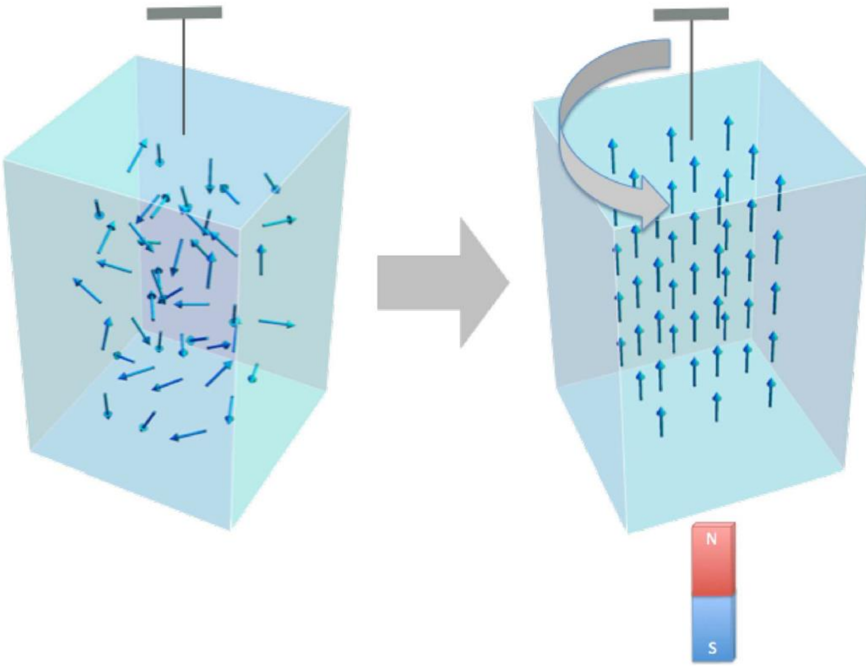
- Phonon spin

- Role of phonons in Einstein-de Haas-like effects

- Long-range phonon spin currents

Einstein, de Haas (1915); picture from Matsuo et al. (2015); modern experiments: detection of compensation point via Barnett effect & spin Seebeck mechanical force (Saitoh group, 2019); classical theory: Assmann/Novak (2019); see also Mentink et al. (2019).

Einstein-de Haas effect



conservation of angular momentum: $M_s V/\gamma \sim I\Omega$

conservation of energy: $\mu_0 M_s B V \gg \Omega^2/I$ **because** $I \propto V^{5/3}$

$\Omega \propto V^{-2/3}$

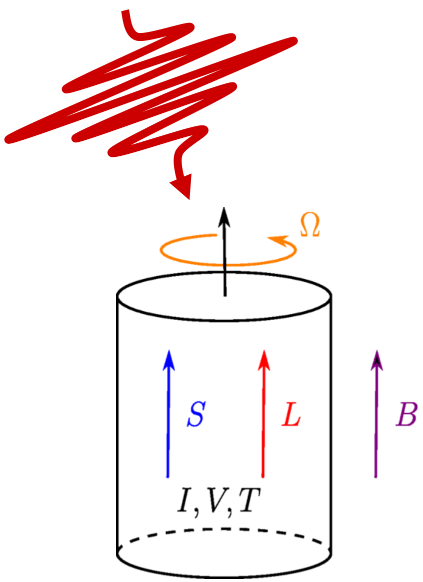
⇨ **<u>Need reservoir = phonons & their spin!</u>**

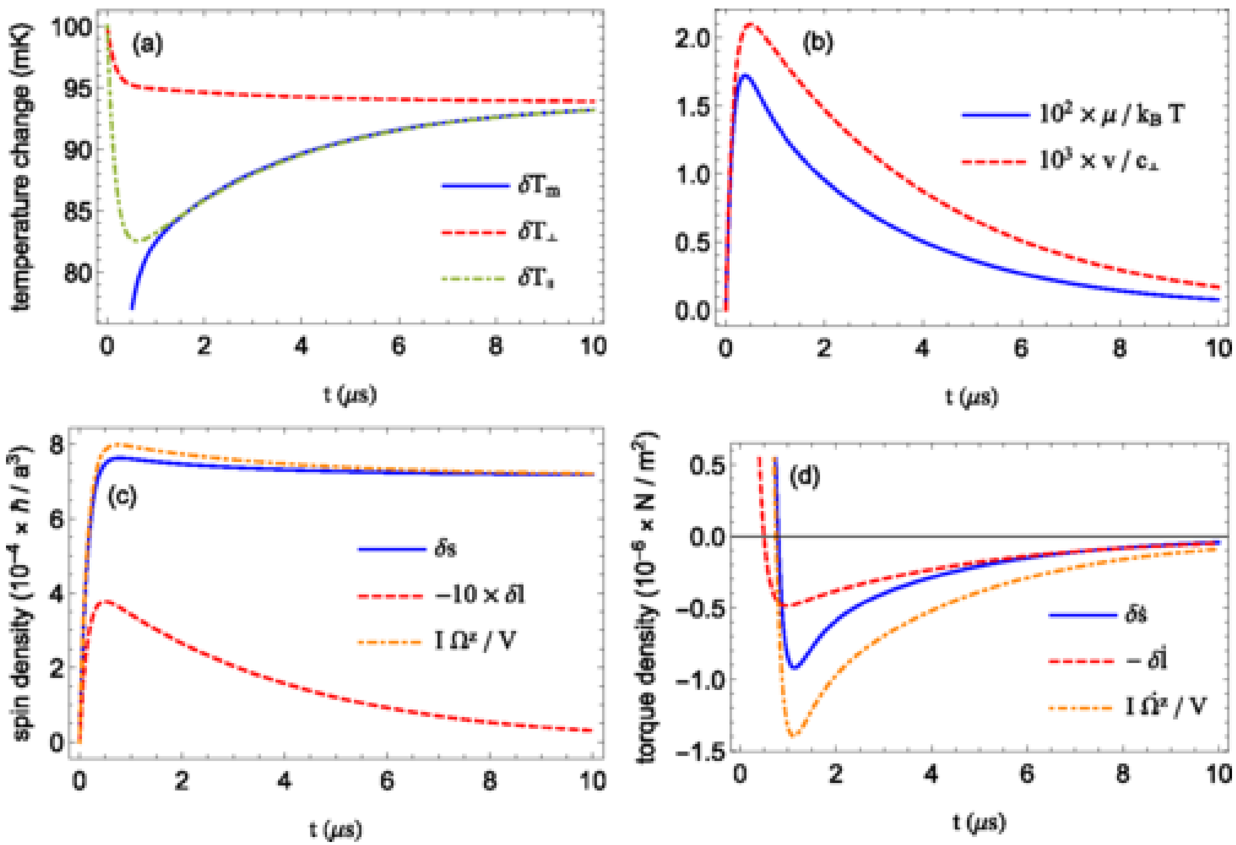
Microscopic theory of Einstein-de Haas-like effects

- Starting point: rotation-invariant Hamiltonian for magnetic insulator
- Split mechanical motion into global rotation & translation + phonons
- Coupled Heisenberg equations for spins, lattice and global rotations
- Approximate as quantum-kinetic theory for magnons and phonons, coupled to magnetization dynamics and global rotation
- Solve by making ansatz in terms of phonon temperature & drift velocity: magnon temperature and chemical potential: $\boxed{\begin{array}{l}\delta T_{\perp}(t), \delta T_{\parallel}(t), v(t) \\ \delta T_m(t), \mu(t)\end{array}}$
- From this, compute change in spin density, phonon spin density and global rotation: $\boxed{\delta s(t), \delta l(t), \Omega^z(t)}$

Phys. Rev. B 101, 104402 (2020)

Results (I)

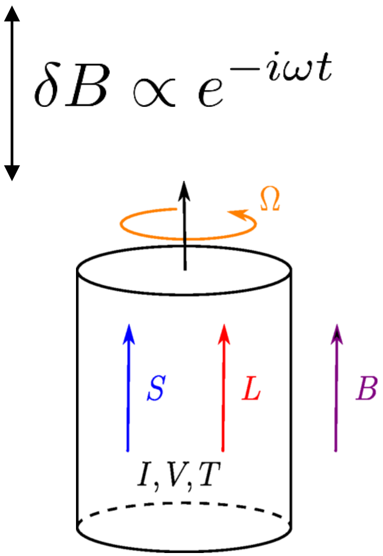


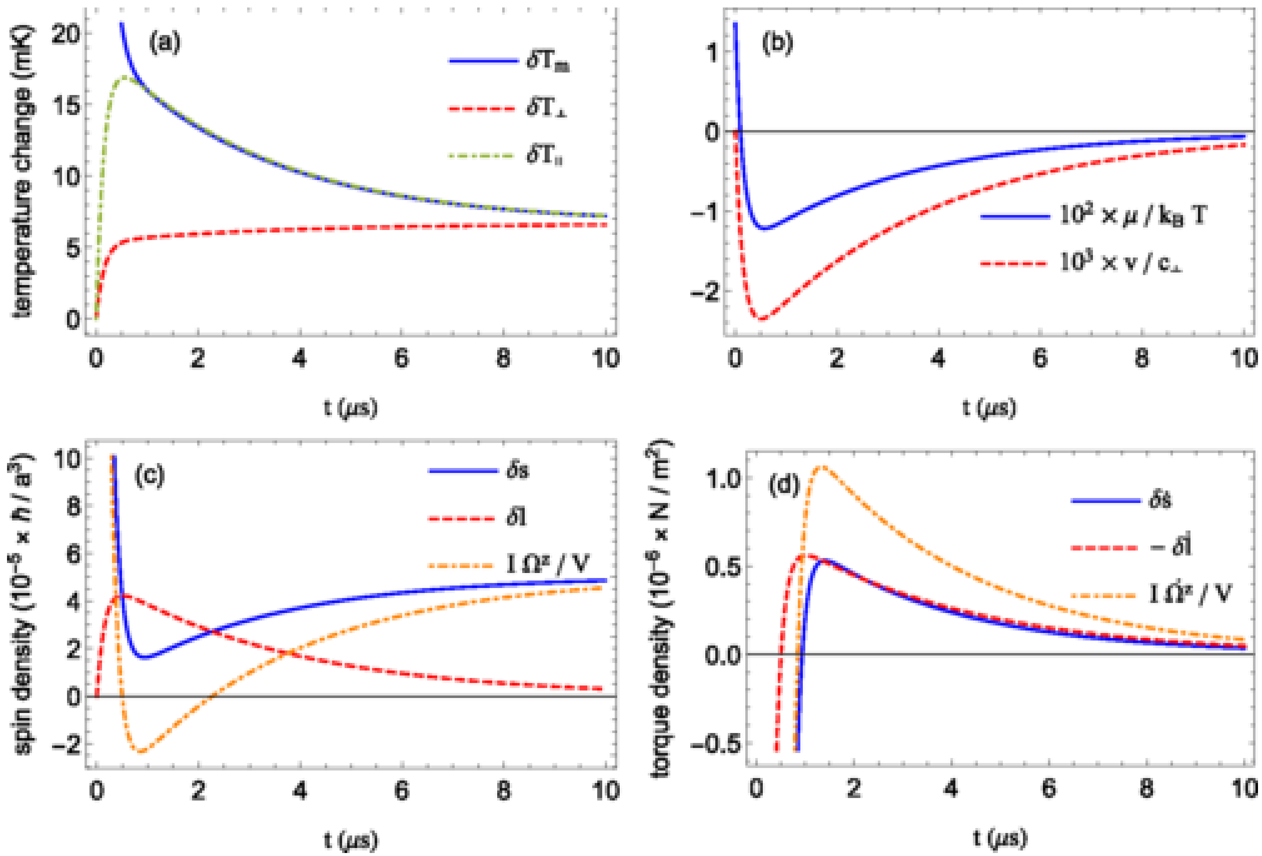


- Initial condition: heating due to laser pulse, angular momentum conserved
- Magnons and longitudinal phonons equilibrate first
- Phonon spin and global rotation compensate for decrease in magnetization

See Schneider et al., Nature Nano. (2020), for a similar scenario to achieve BEC

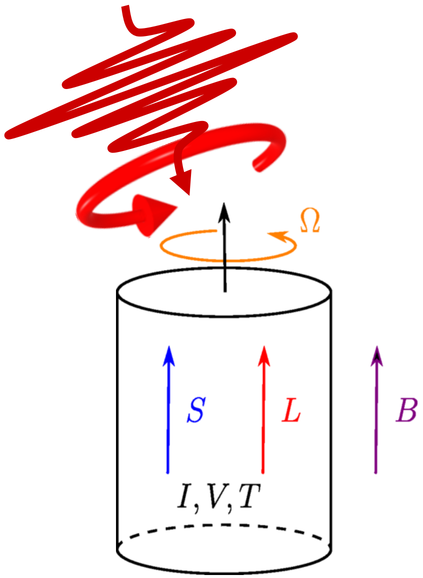
Results (II)

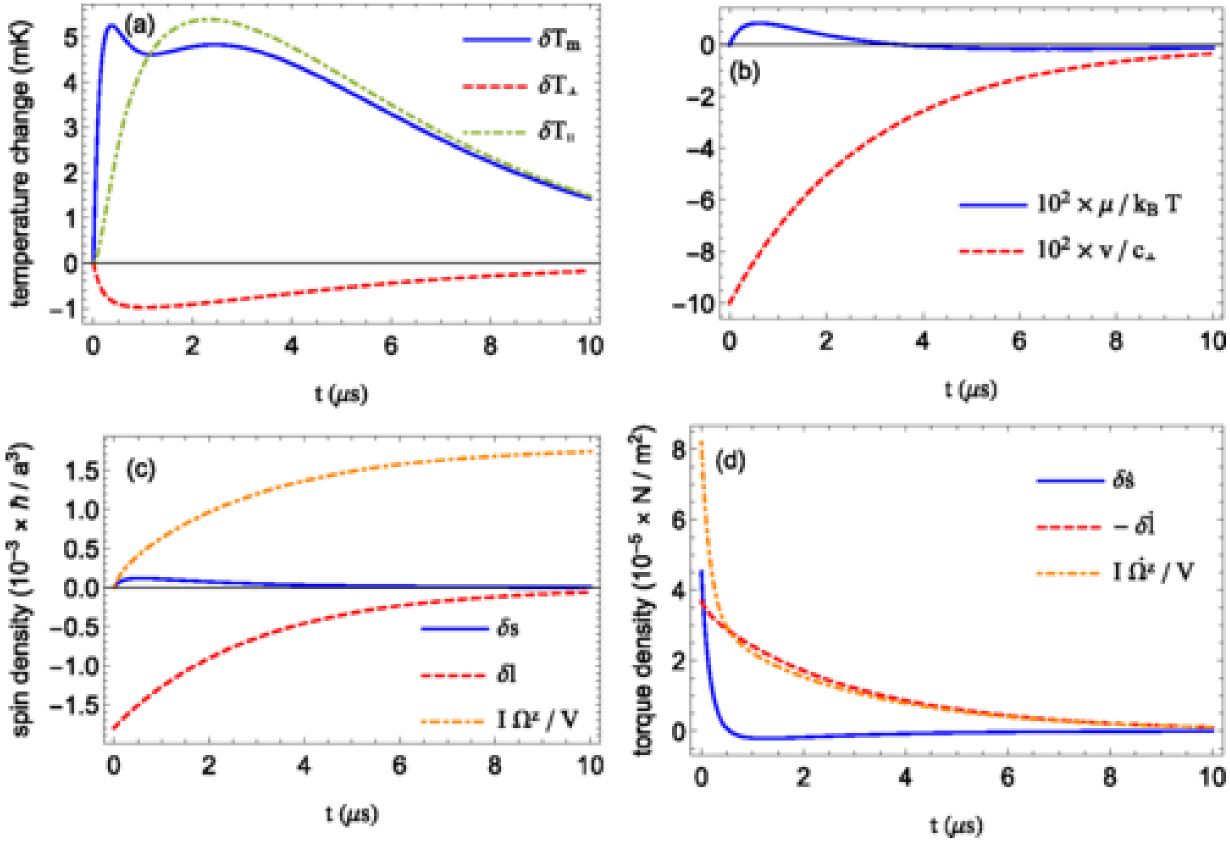




- Initial condition: parallel pumping, angular momentum conserved
- Magnons and longitudinal phonons equilibrate first
- Phonon spin and global rotation result due to equilibration with magnons
- Phonon spin large, global rotation changes sign

Results (III)





- **Initial condition: (optical) spin injection into phonons**
- **Magnons and longitudinal phonons equilibrate first**
- **Magnon spin hardly changes, phonons and global rotation dominate**

Outline

- Phonon spin

- Role of phonons in Einstein-de Haas-like effects

- Long-range phonon spin currents

Outline

- Phonon spin

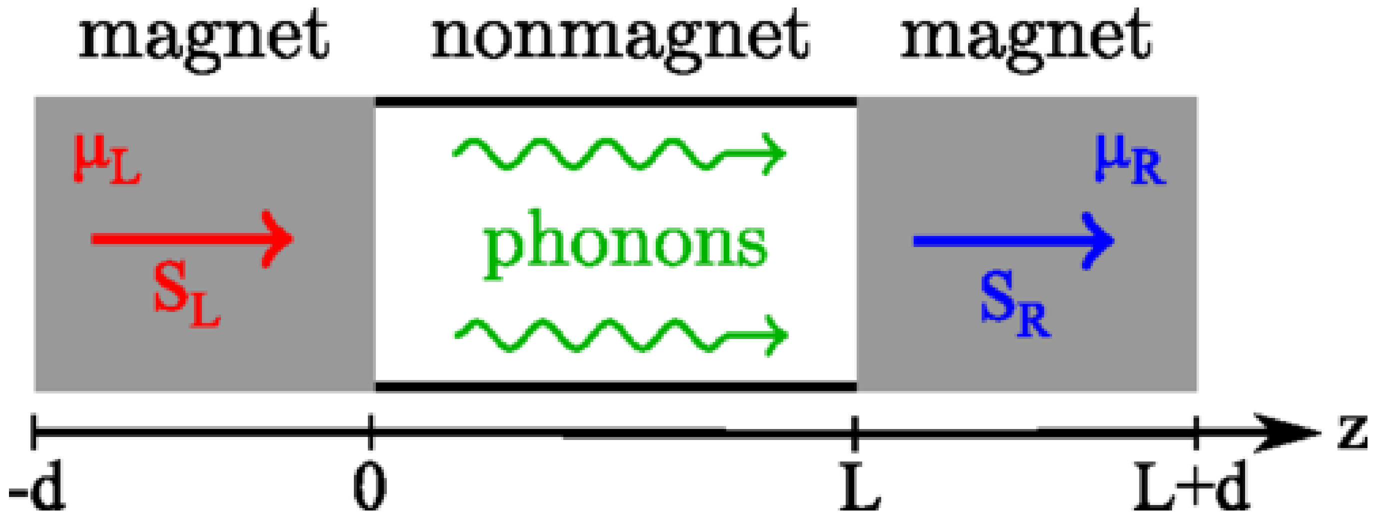
- **Role of phonons in Einstein-de Haas-like effects – conclusion: phonons & their spin important, but what can we do with them?**

- Long-range phonon spin currents

Outline

- Phonon spin
- Role of phonons in Einstein-de Haas-like effects – conclusion: phonons & their spin important, but what can we do with them?
- **Long-range phonon spin currents**

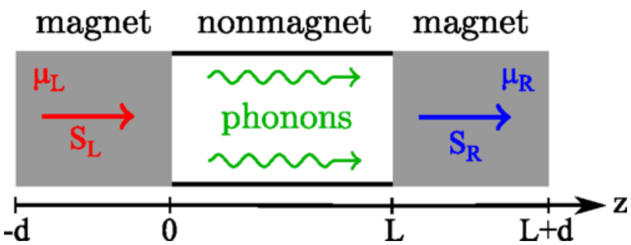
Set-up

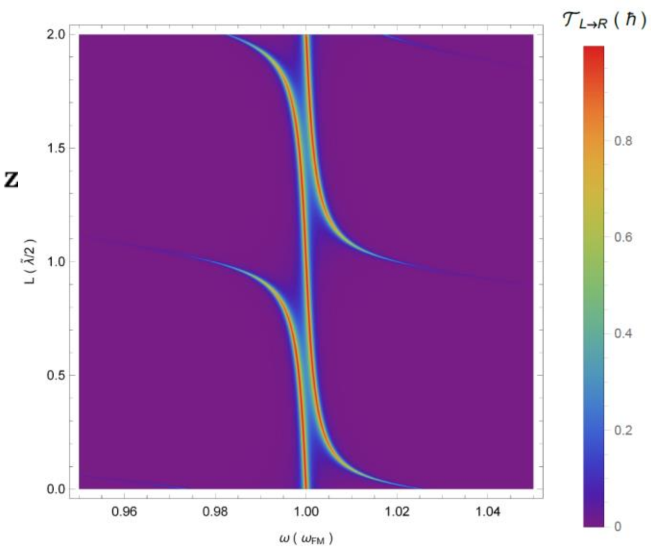


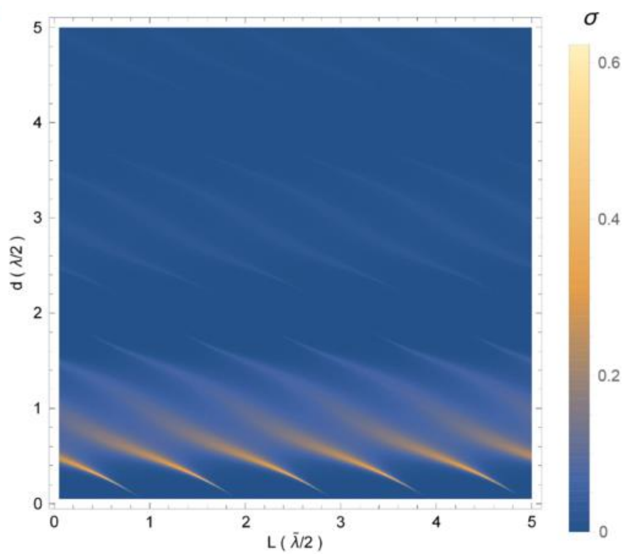
- Incoherently driven magnetic reservoirs
- Non-magnetic insulator
- Spin transfer due to magnetoelastic interactions
- Theorical approach: coupled stochastic equations for magnetic and lattice dynamics

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

Spin-conductance & resonance condition







spin current:

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

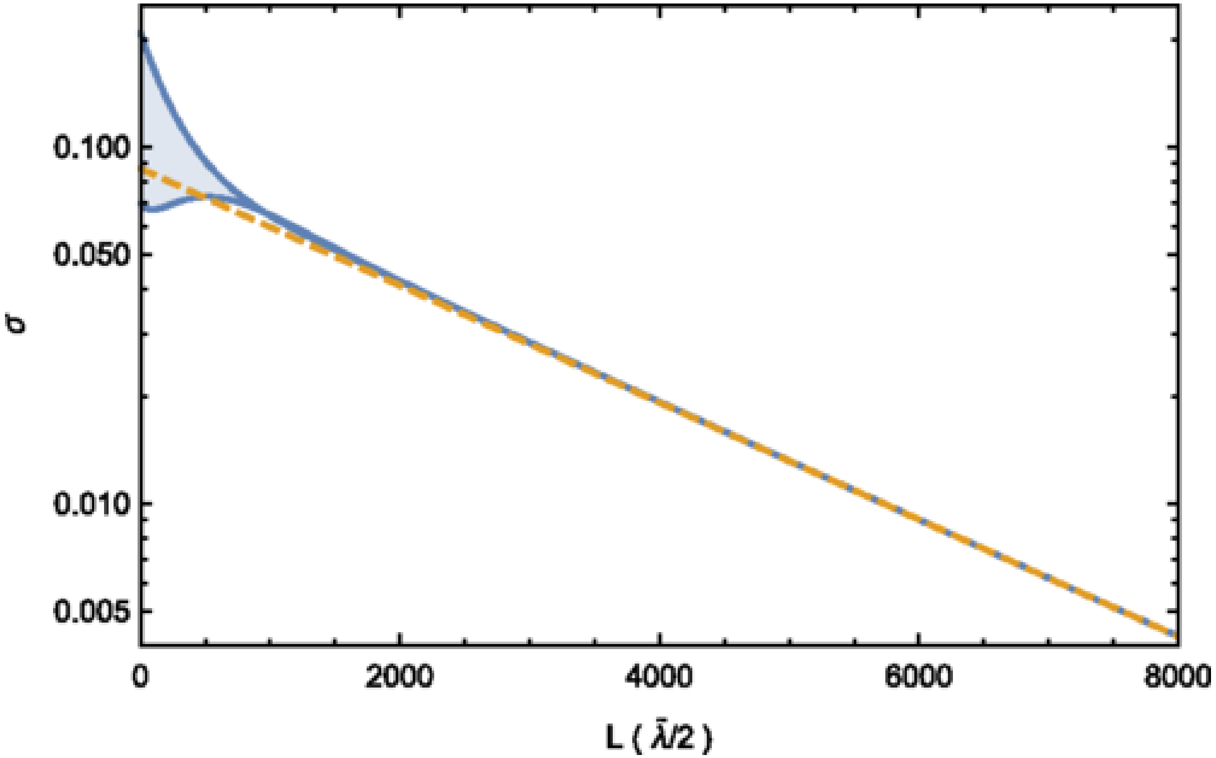
for small bias:

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

resonance condition

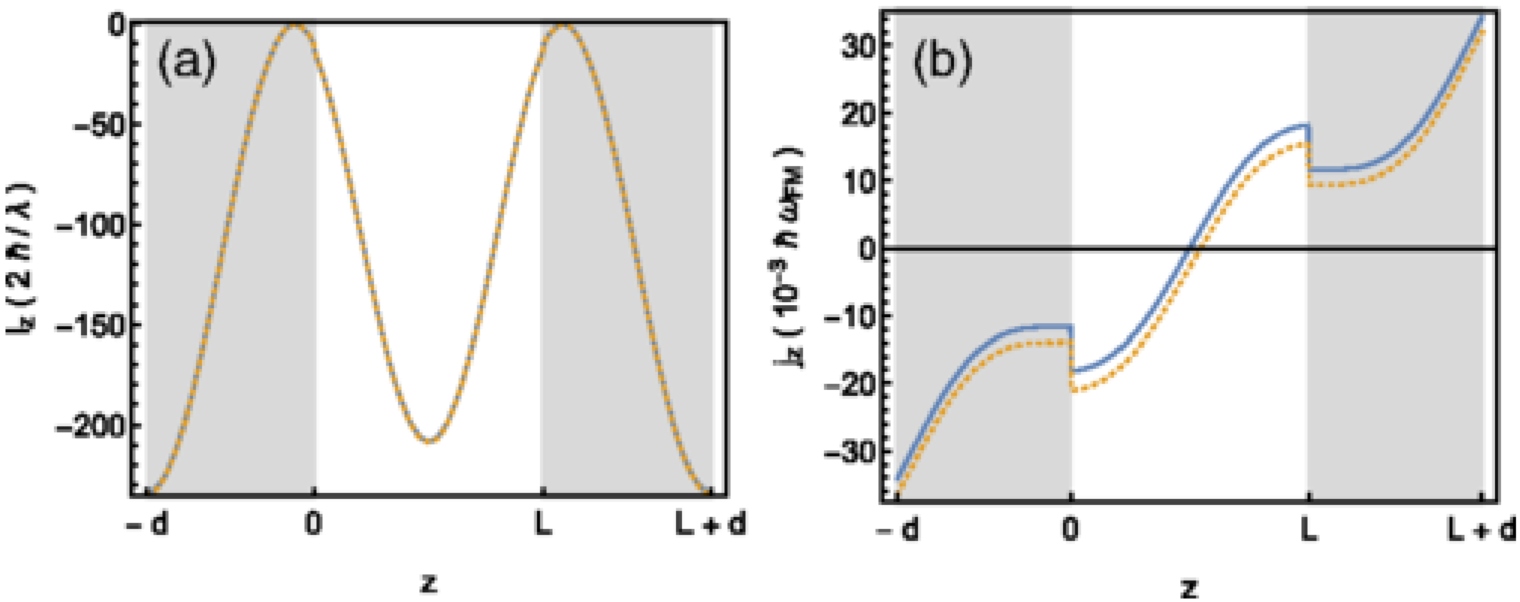
$$L/(\tilde{\lambda}/2) + 2d/(\lambda/2) = \text{integer}$$

Long-range phonon spin currents



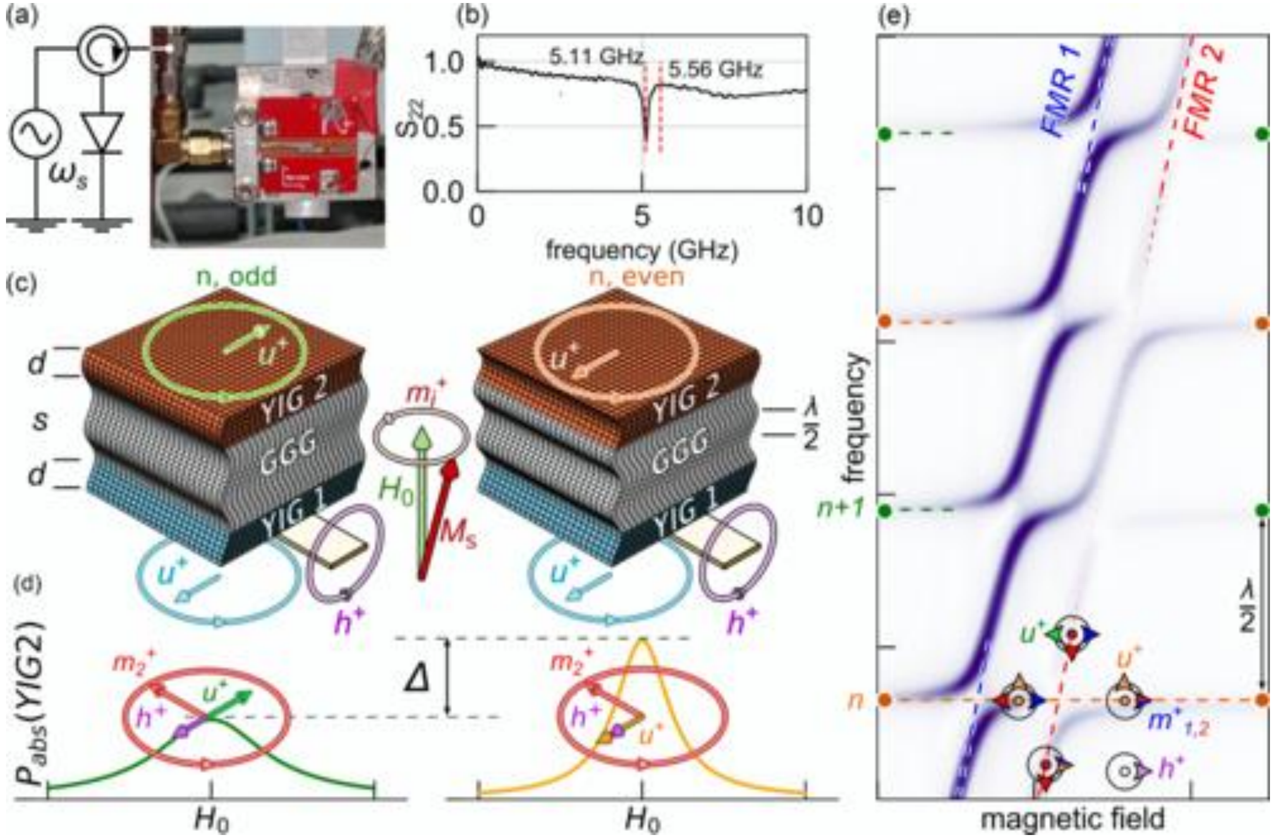
- YIG and GGG parameters
- Decay length ~ 1 mm

Phonon spin accumulation & spin current



- **Same order of magnitude as spin density related to magnetization**
- **(Quasi-)equilibrium phonon spin accumulation and phonon spin currents**

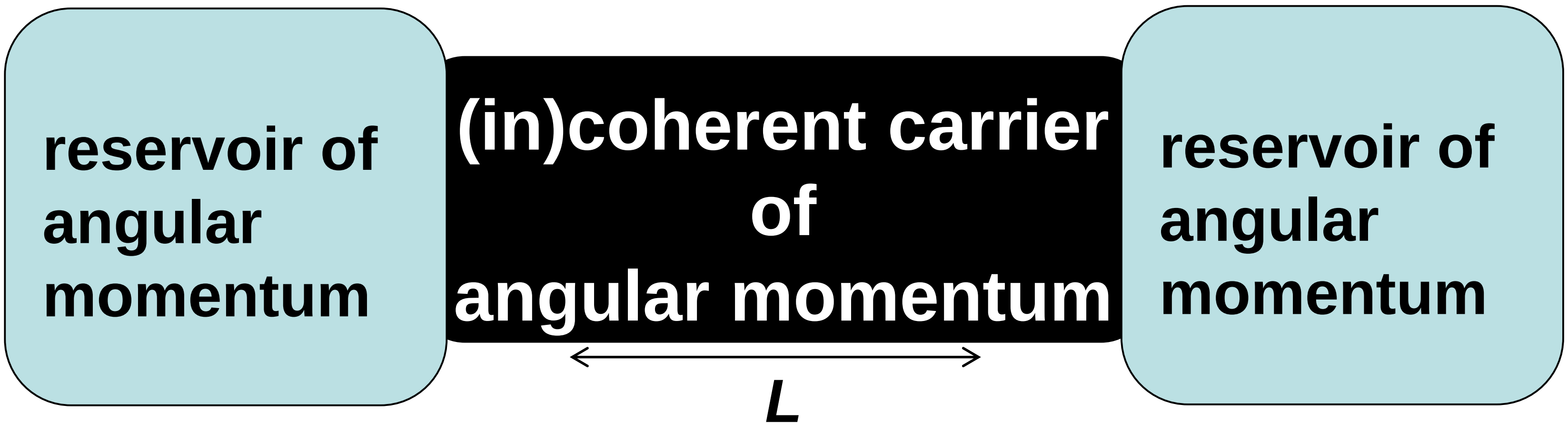
Experiments in coherent regime



FMR experiment, coherent coupling

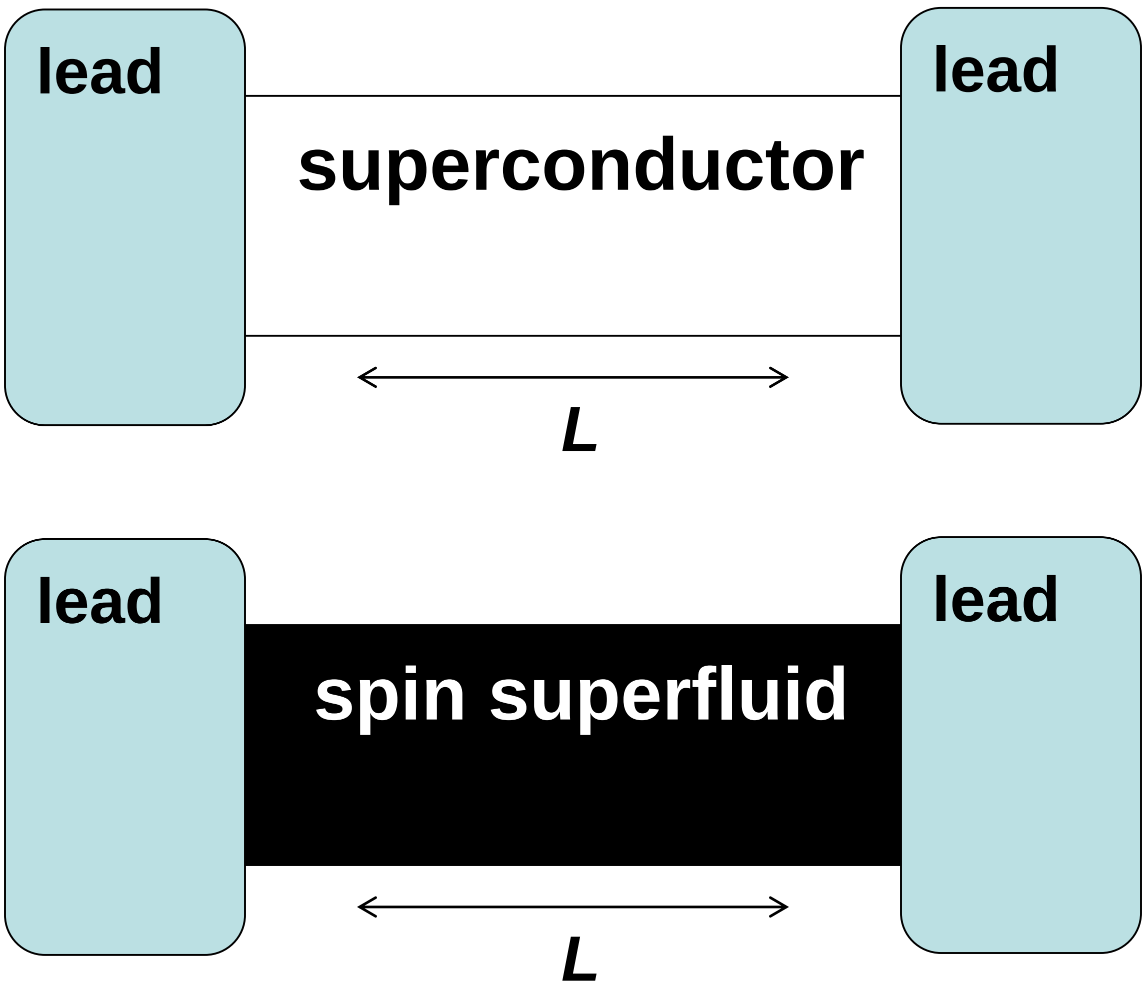
An et al. Phys. Rev. B (2020), motivated by Streib et al. (2018)

Conclusion



- Electrons (100’s nm); limited by spin-orbit and disorder
- Magnons (10’s μm); limited by magnetic quality
- <u>This talk: phonons (mm’s); limited by acoustic quality</u>
- Experiments?!

Long-term motivation



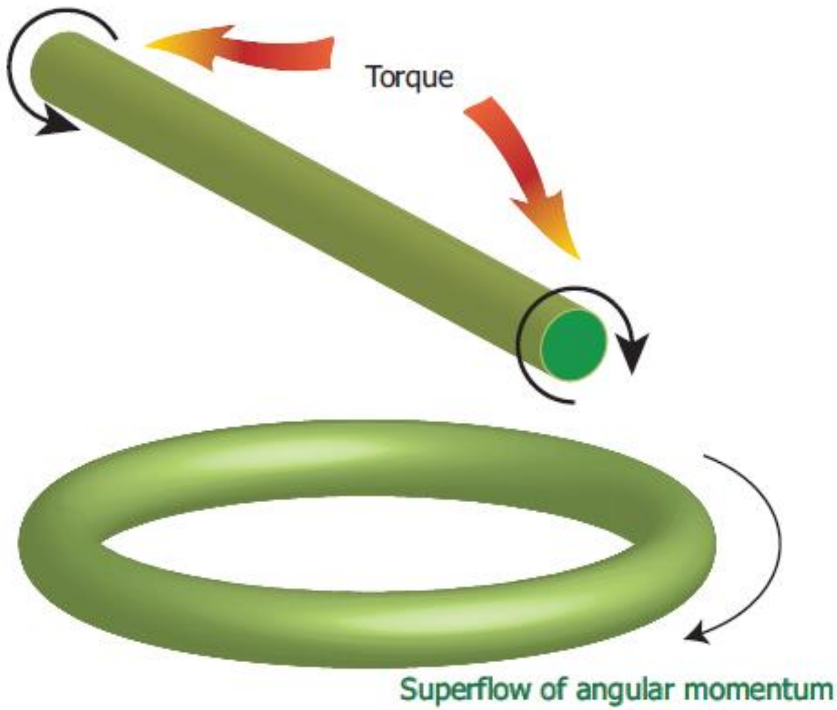
$I=V/R$ with
R independent of L

below room T

?

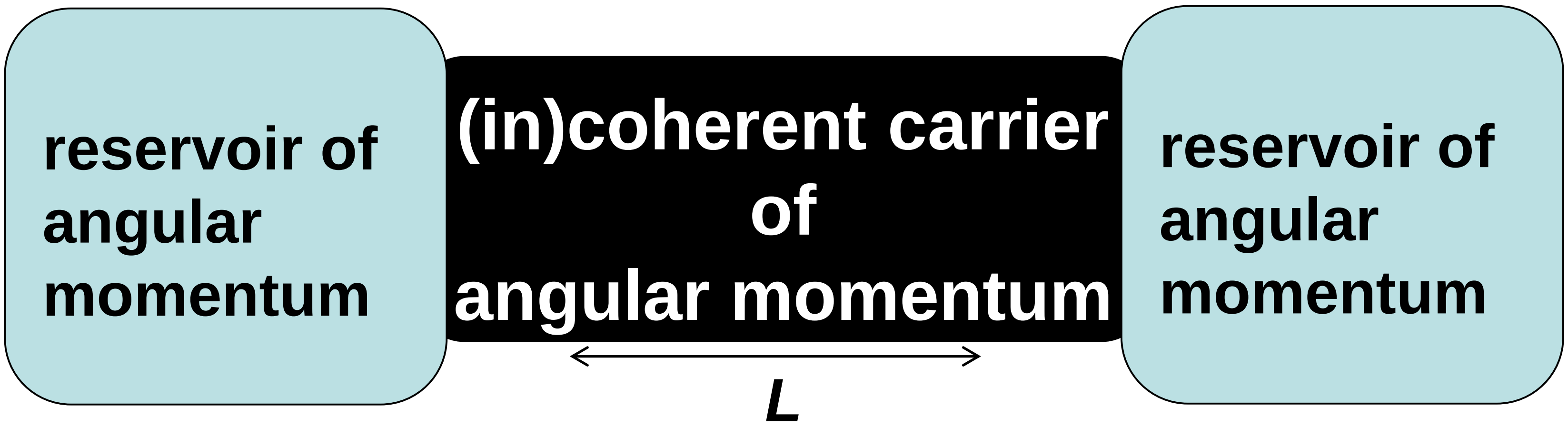
above room T?

Superfluid transport of angular momentum without magnetization



Sonin (2010)

Conclusion



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