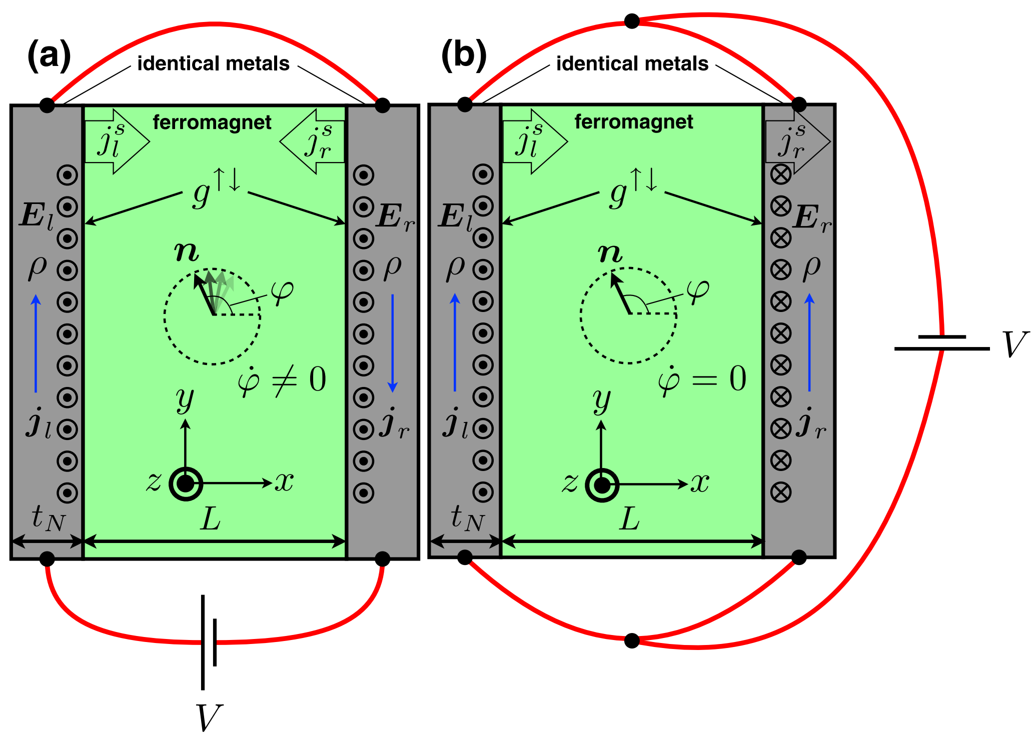
Collective spin transport in insulators

(its microwave dynamics and coupling to thermoelectricity and quantum impurities)



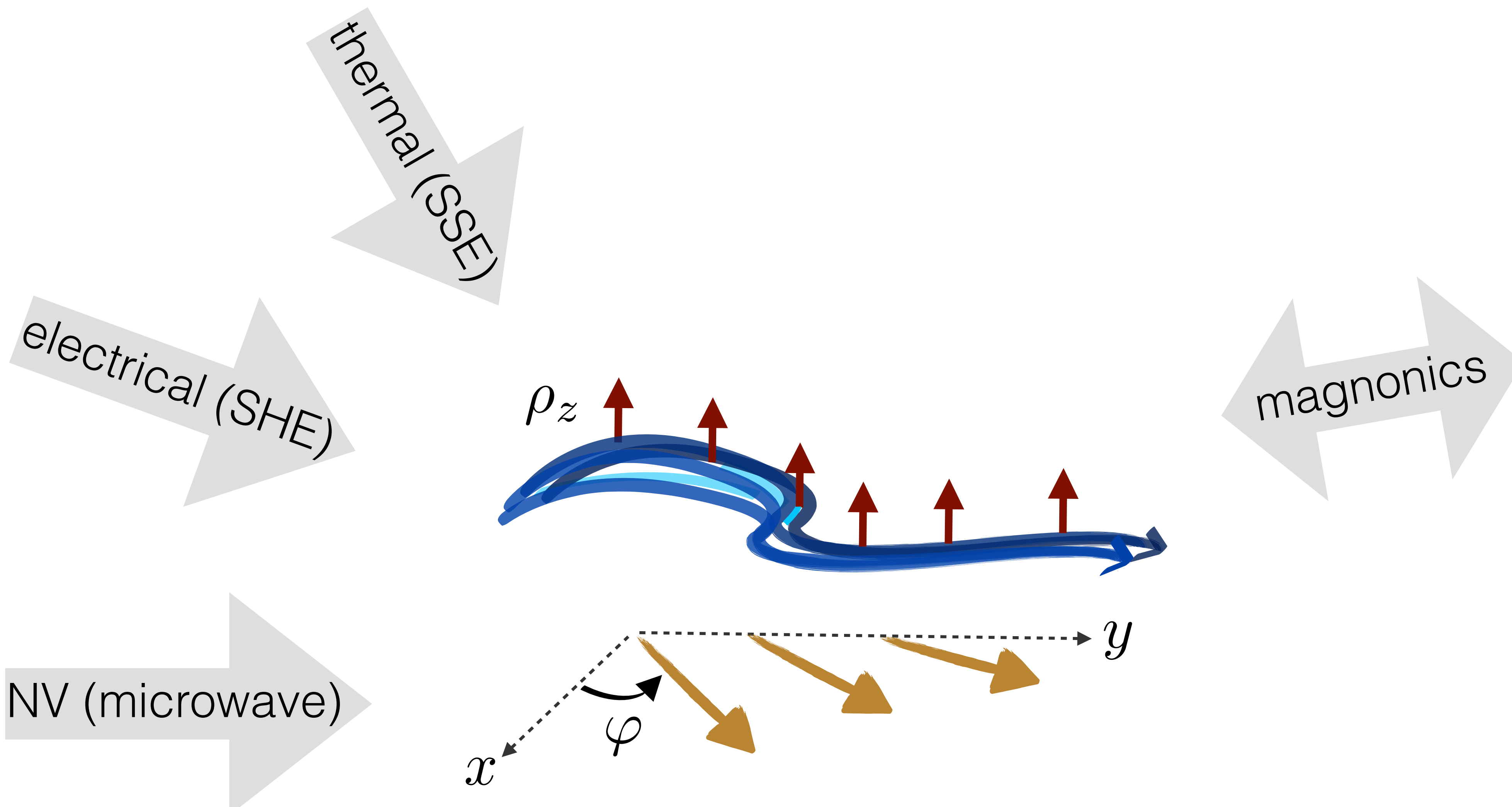
Yaroslav Tserkovnyak

UCLA

in collaboration with

Scott Bender (UCLA → Utrecht), Benedetta Flebus (Utrecht → UCLA), So Takei (UCLA → CUNY), Pramey Upadhyaya (UCLA → Purdue), Se Kwon Kim, Hector Ochoa, and Ricardo Zarzuela (UCLA), Rembert Duine (Utrecht), Ilya Krivorotov (UC Irvine), Bert Halperin and Amir Yacoby (Harvard)

Magnetic insulators as signal transducers



coherent order-parameter dynamics
(from *two-fluid superfluidity* to *topological hydrodynamics*)

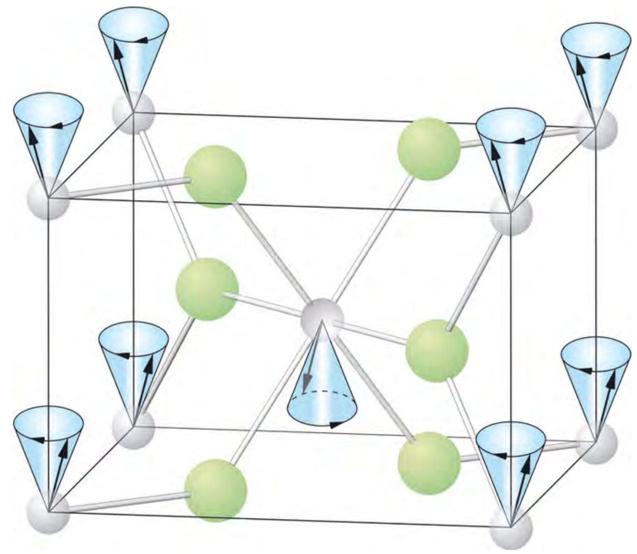
magnetic-insulator island as a coherent microwave "cavity"

Outline

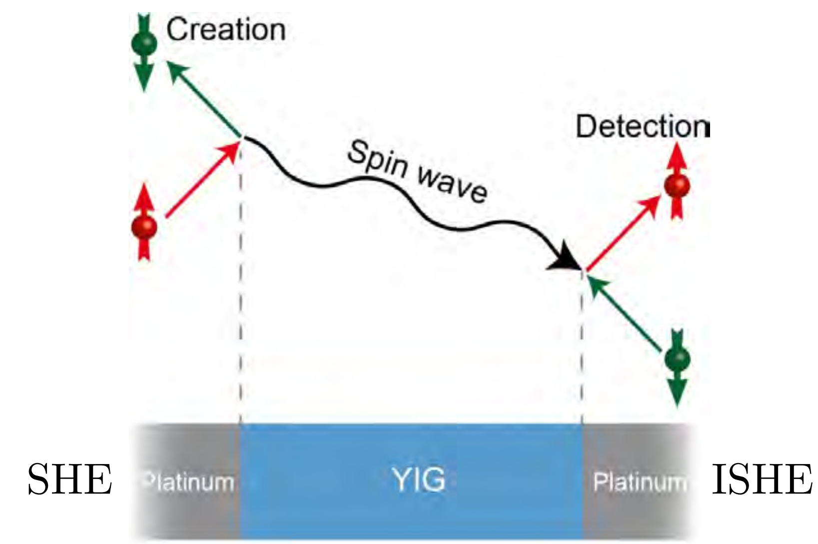
- Magnetic insulators as a transport medium: *The two-fluid way*
- Easy-plane spin dynamics
    - Spin condensates: Natural and (thermoelectrically) pumped
- Microwave regime of collective spin transport
  - (Approximately) easy-plane magnets
  - Triplet superconductors
- Glassy spin superfluidity

Excitations of ordered media

- Spin waves (Goldstone modes)



elementary excitations of a spin-ordered state
(coherent and thermal)

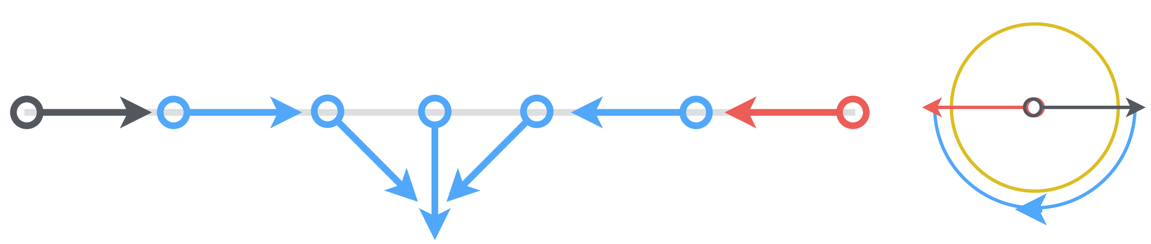


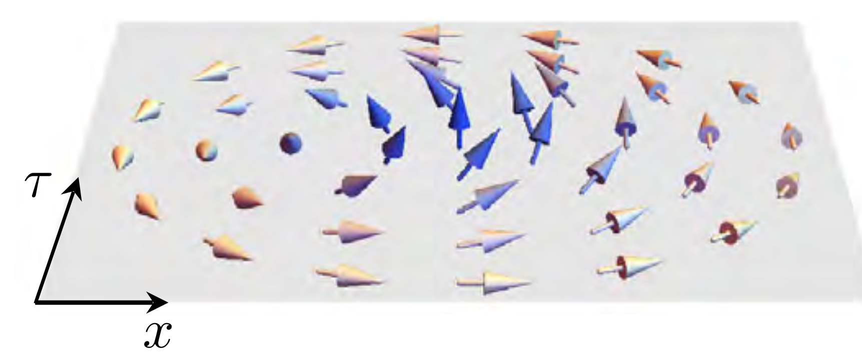
gaseous medium for spin transport

(incoherent bias)

Cornelissen, van Wees *et al.*, *Nature Mat.* (2015)

- Topological textures (and topological defects) $\rightarrow$ long-ranged transport

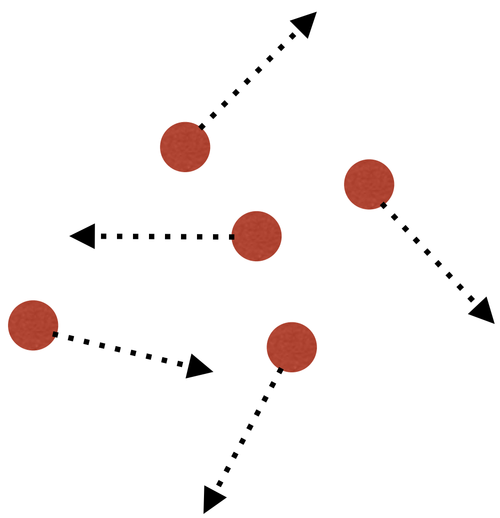




(condensates and superfluid states)

Two types of flows

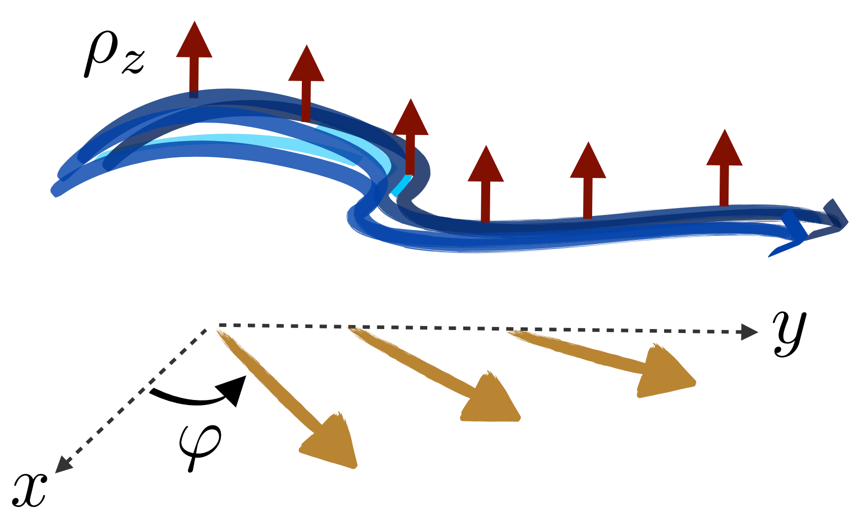
- Particle-like hydrodynamics



$$\partial_t \rho + \nabla \cdot \mathbf{j} = 0$$ - continuity equation according to the particle number conservation

$$\mathbf{j} \propto \nabla(\mu, T)$$ - the quasiequilibrium state is locally parametrized by temperature and chemical potential

- Coherent order-parameter dynamics



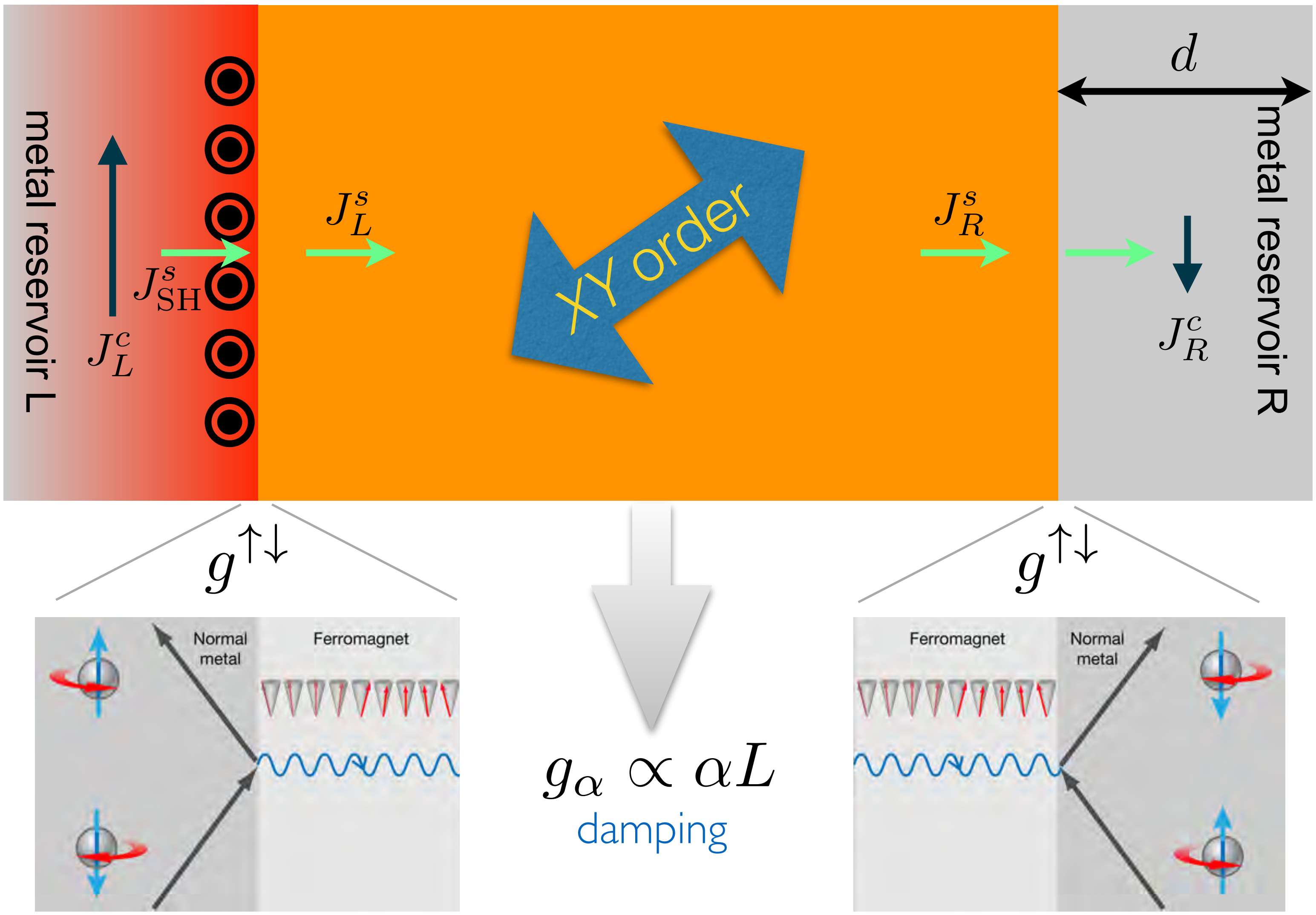
(easy-plane "spin superfluid")

$$\partial_t \rho + \nabla \cdot \mathbf{j} = 0$$ - continuity equation according to the particle number conservation

$$\mathbf{j} \propto \nabla\varphi$$ - the coherent flow is rooted in the order-parameter rigidity

Halperin and Hohenberg, *PR* (1969); Sonin, *JETP* (1978)

An elementary circuit based on the winding flow



large long-ranged (algebraic) transconductance

$$J_s \propto \frac{(g^{\uparrow\downarrow})^2}{2g^{\uparrow\downarrow} + g_\alpha}\mu$$

$g_\alpha \rightarrow L$

Takei and YT, *PRL* (2014)

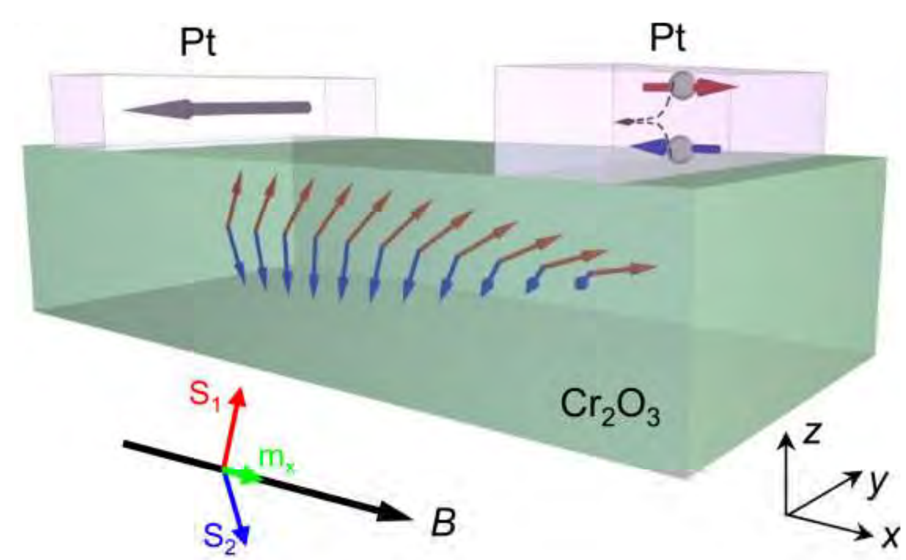
Bauer and YT, *Physics* (2011)

SCIENCE ADVANCES | RESEARCH ARTICLE

PHYSICS

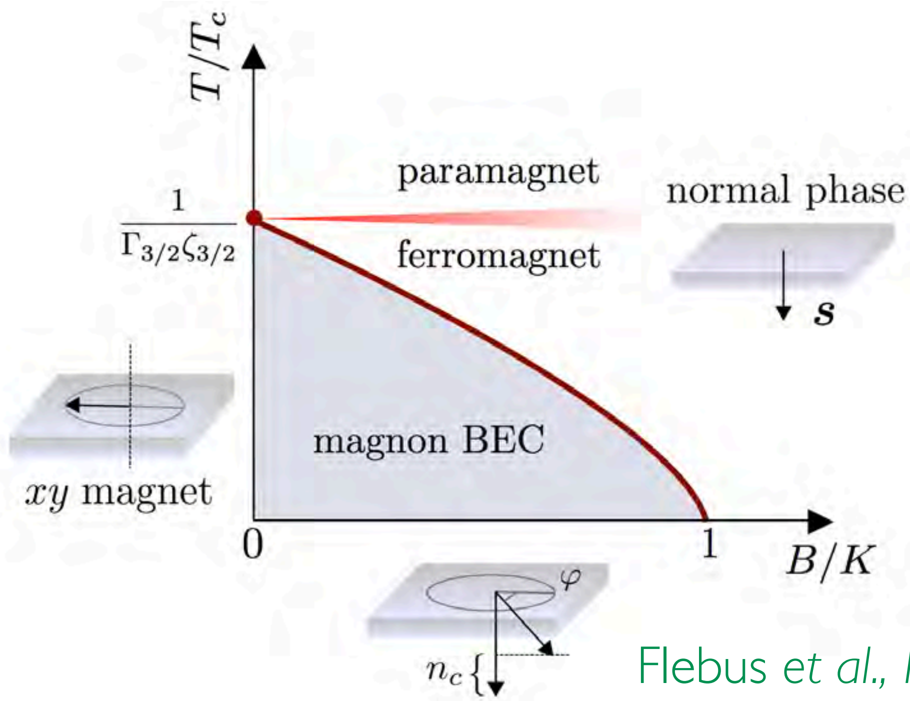
Experimental signatures of spin superfluid ground state in canted antiferromagnet Cr_2O_3 via nonlocal spin transport

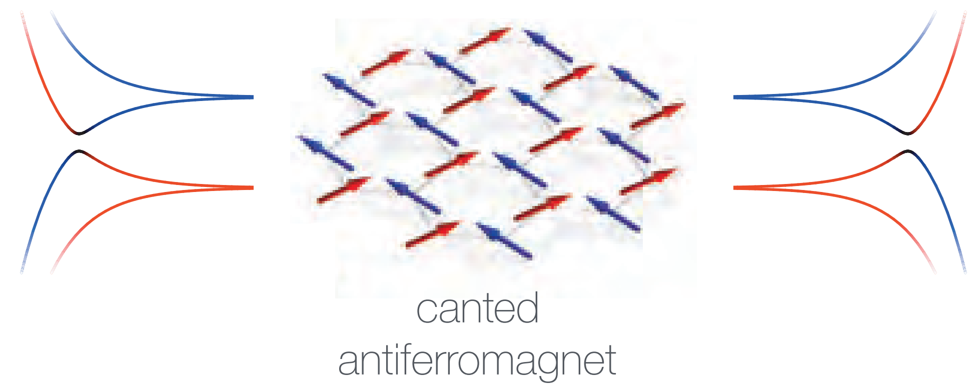
Wei Yuan,[1,2] Qiong Zhu,[1,2] Tang Su,[1,2] Yunyan Yao,[1,2] Wenyu Xing,[1,2] Yangyang Chen,[1,2] Yang Ma,[1,2] Xi Lin,[1,2] Jing Shi,[3]* Ryuichi Shindou,[1,2] X. C. Xie,[1,2]* Wei Han[1,2]*



Equilibrium magnon condensates

- Easy-plane magnet

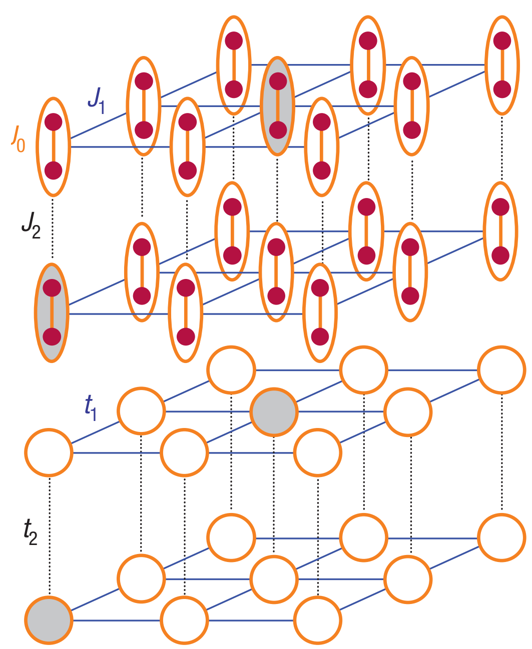


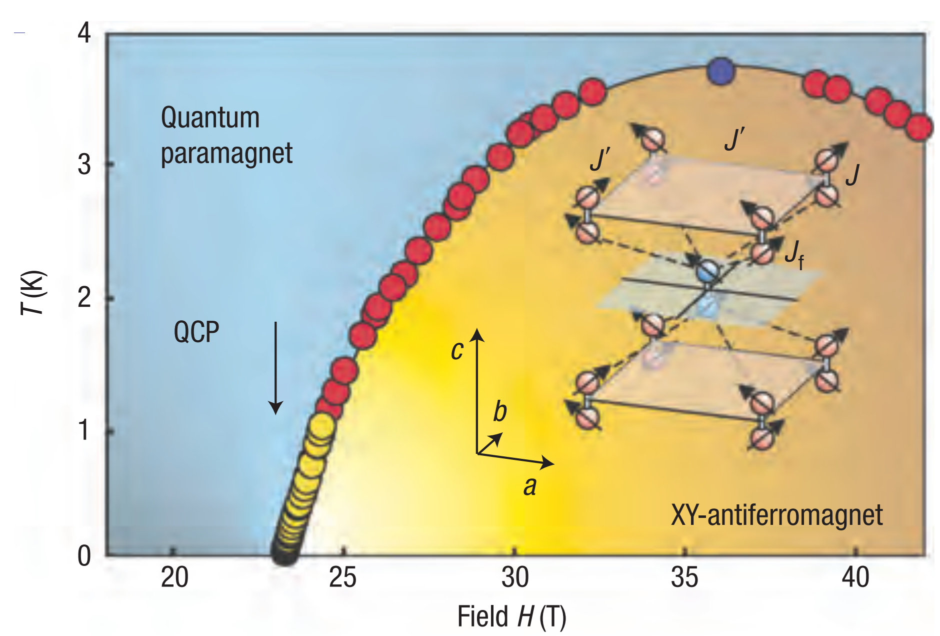


spin-flopped Cr_2O_3, MnF_2, ... $\nu = 0$ QH graphene

Flebus *et al.*, *PRL* (2016)   Takei *et al.*, *PRL* (2016)

- Triplon condensates



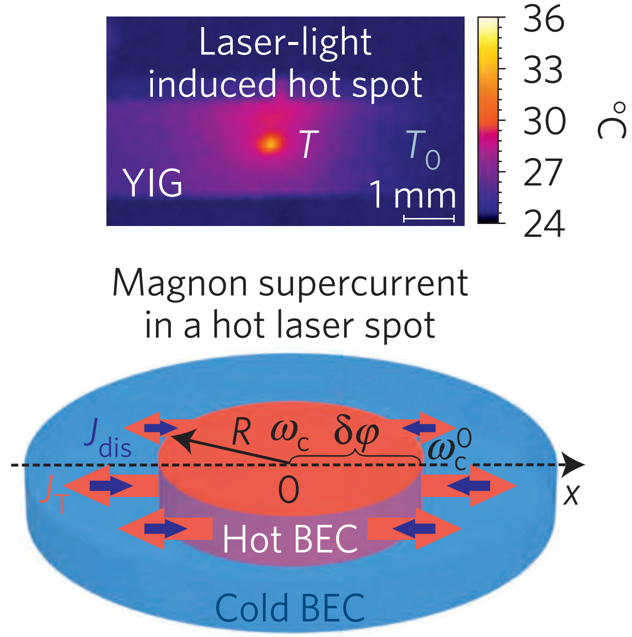


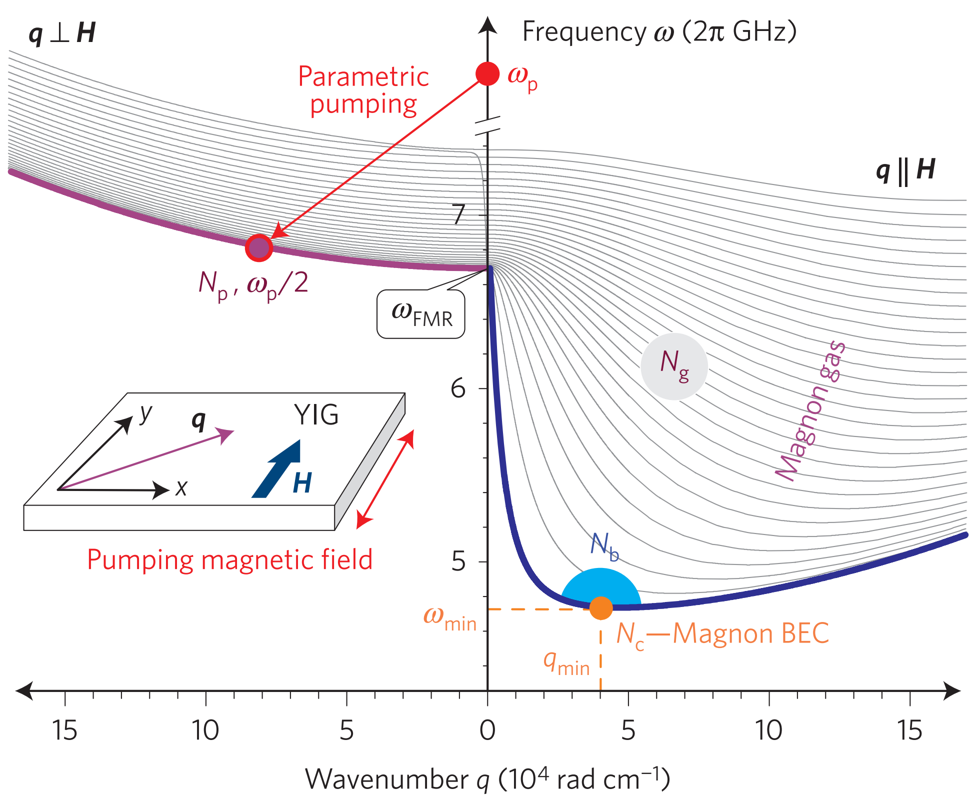
$TlCuCl_3$, $BaCuSi_2O_6$

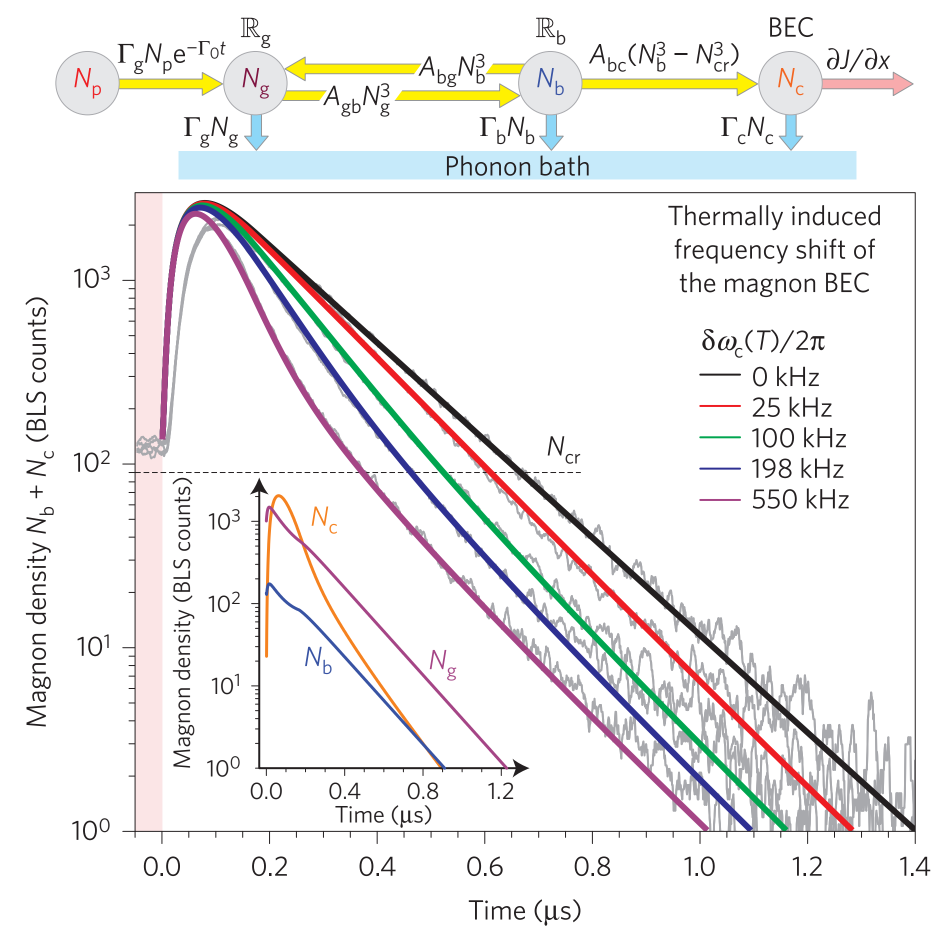
Giamarchi *et al.*, *Nature Phys.* (2008)

Pumped condensates

- Parametric microwave pumping (probed by BLS)

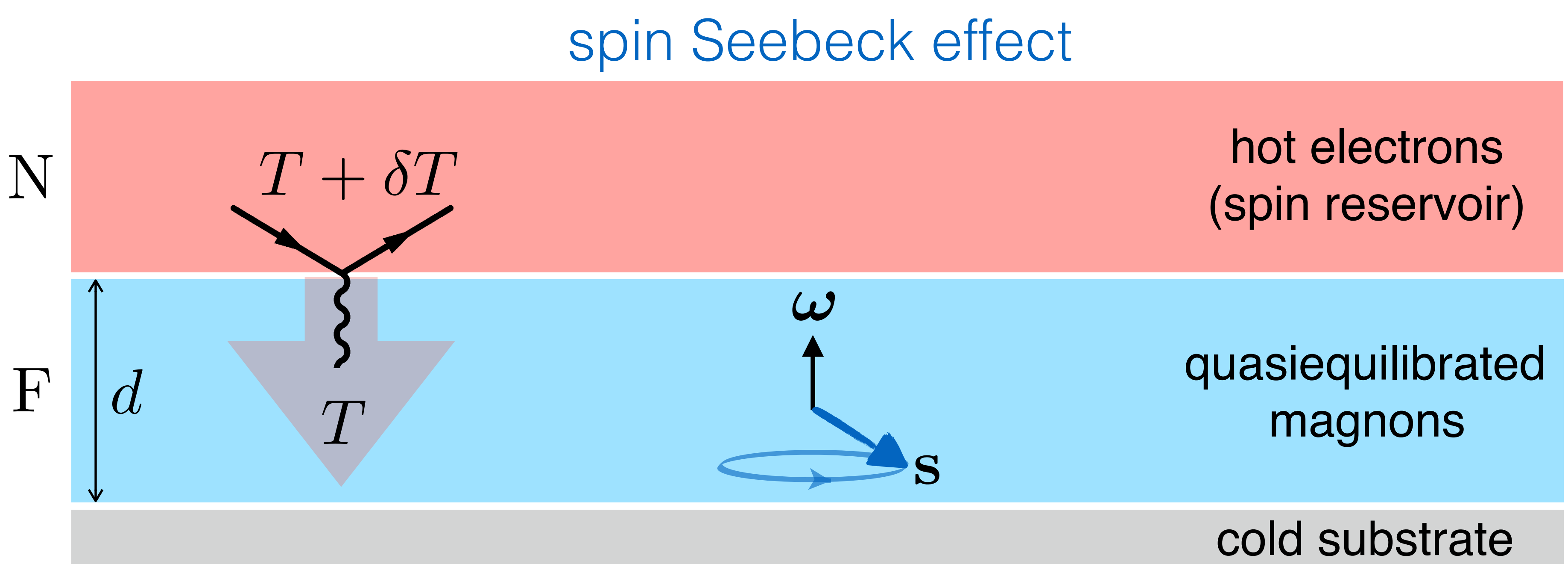




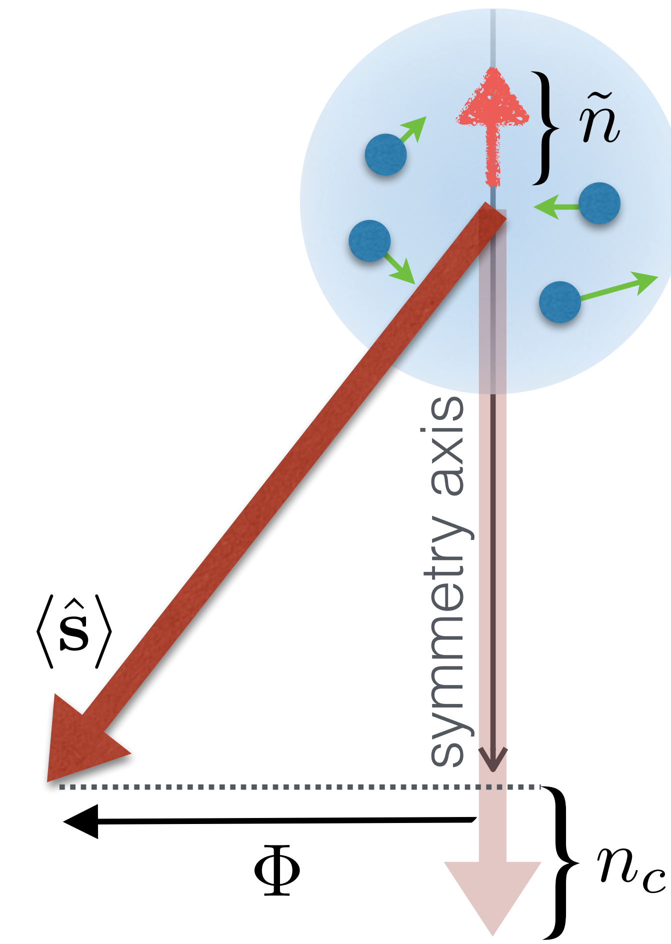


Demokritov, Hillebrands, Serga, Bozhko *et al.*, *Nature* (2006) - *Nature Phys.* (2016)

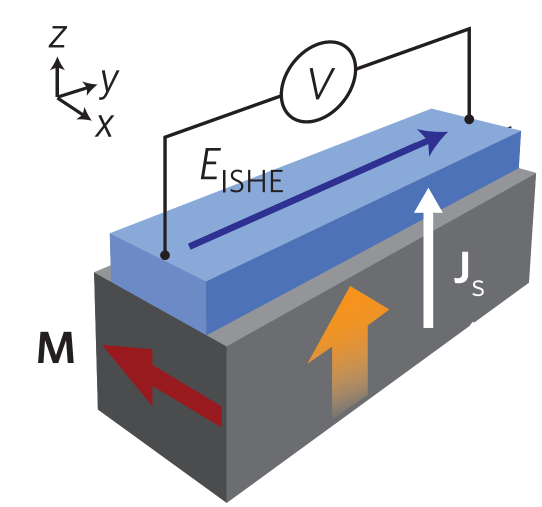
Thermal pumping in thin films



Bender, Duine, and YT, *PRL* (2012) and *PRB* (2014)



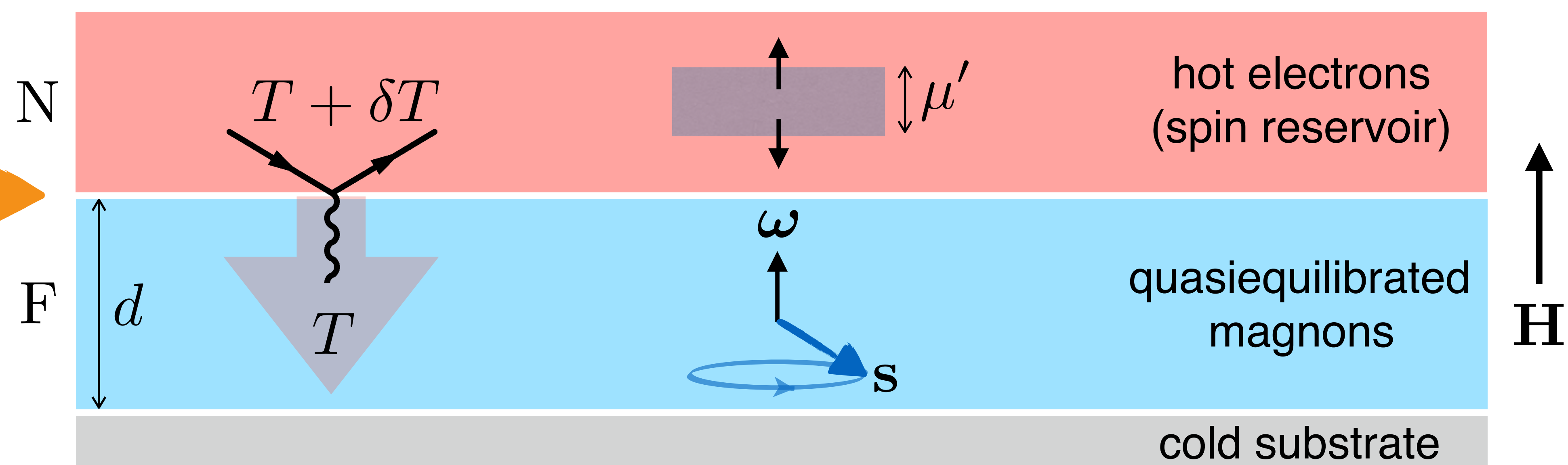
- Inject energy and spin from the hot electron side
- Extract energy from the cold electron side
- Supposing the magnons equilibrate internally sufficiently fast, the oversaturated thermal cloud precipitates at a critical thermal bias



Uchida, Saitoh *et al.*, *APL* (2010)

Electron/magnon-torque instabilities

$$\alpha' = \frac{g^{\uparrow\downarrow}}{4\pi s d}$$



$$\dot{n}_c = -\frac{n_c}{\tau} - \Gamma/\hbar$$

electrically controlled

$$\frac{1}{\tau} = 2\alpha'(\hbar\omega - \mu') + 2\alpha\omega$$

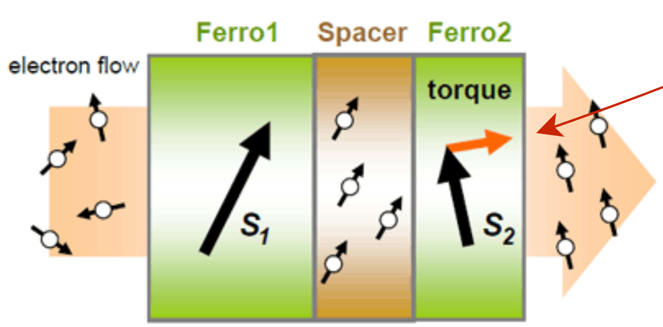
electronic torques

Gilbert damping

thermally controlled

$$\Gamma = 2\eta(\hbar\omega - \mu)n_c$$

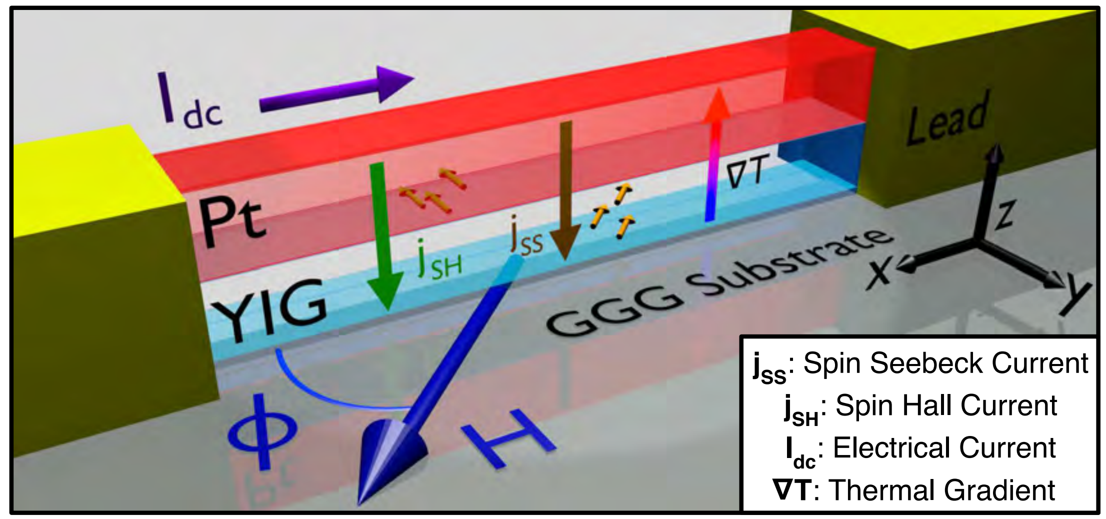
magnonic torques

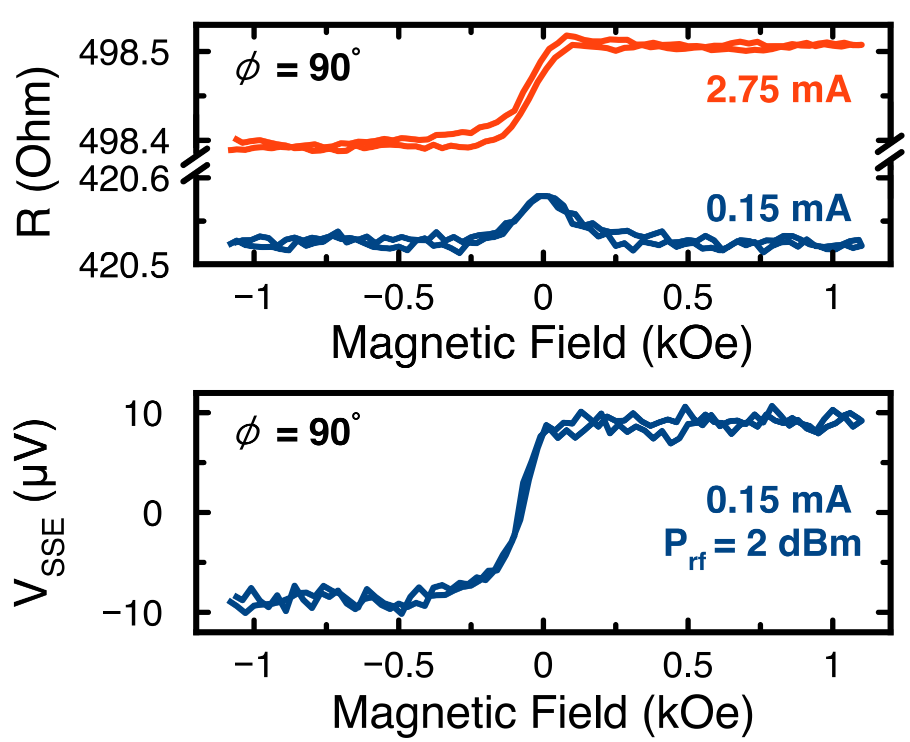


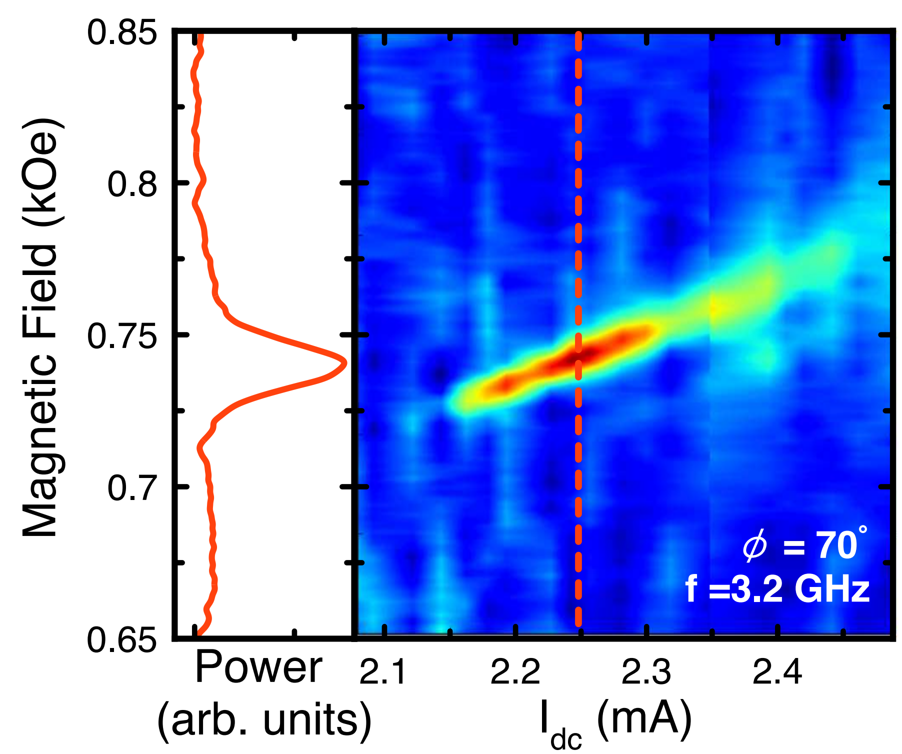
Mizukami Lab

Bender, Duine, and YT, *PRL* (2012) and *PRB* (2014)

Spin-caloritronic nano-oscillator

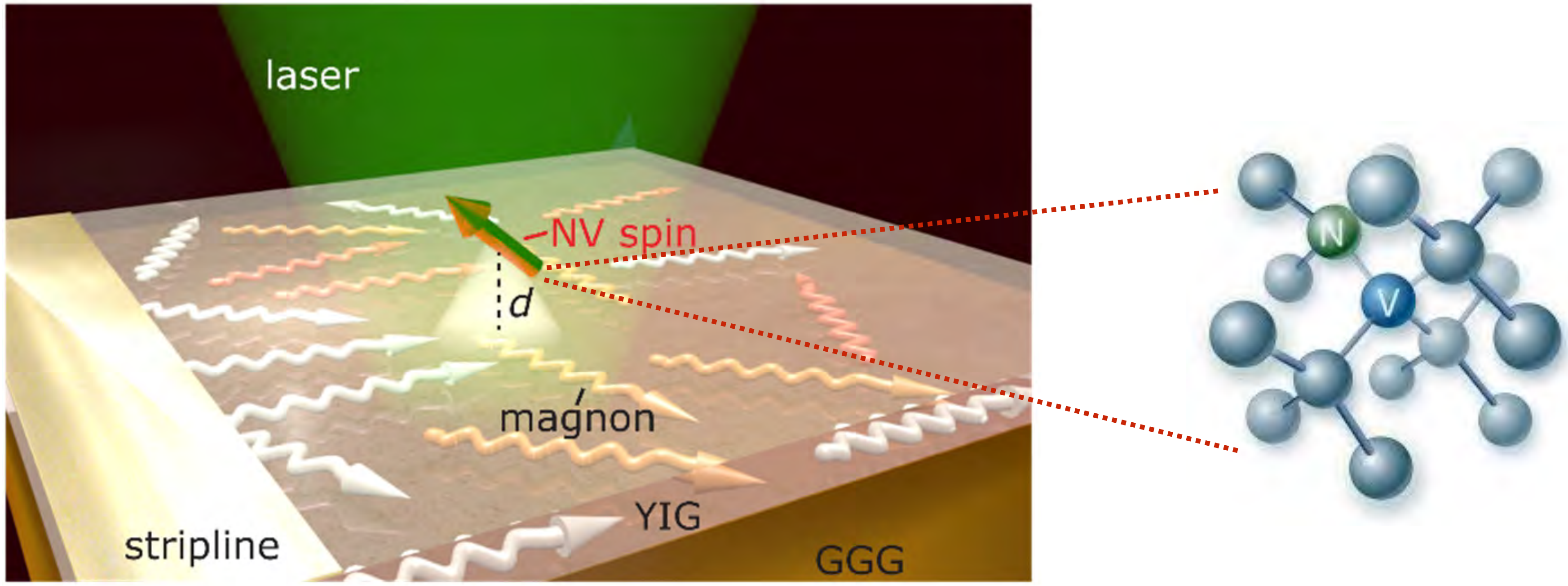


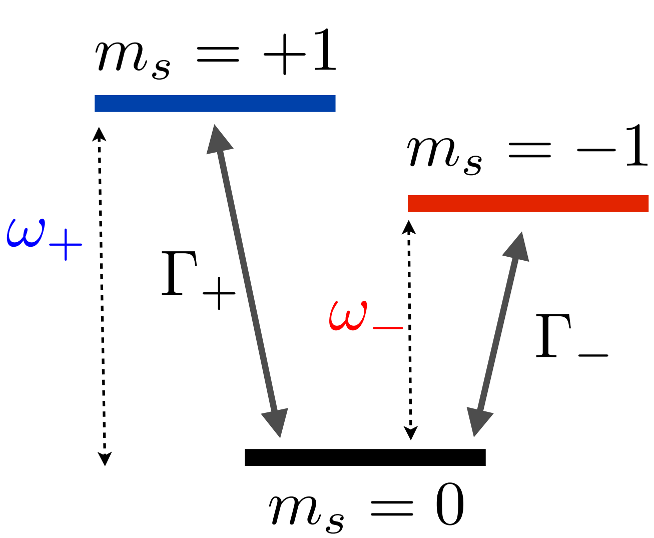


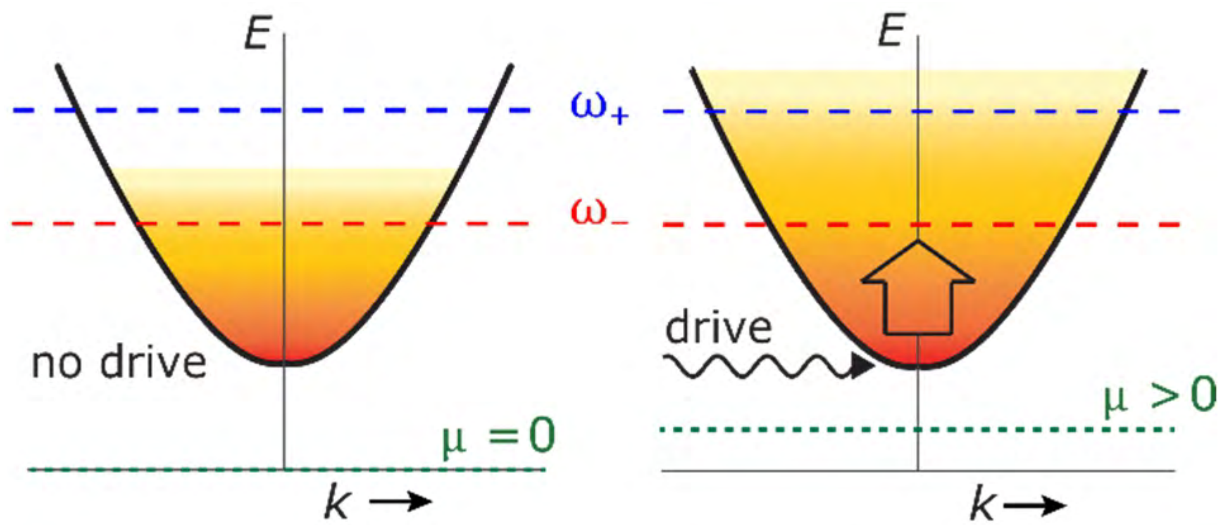


Safranski, Barsukov, YT, Wu, Krivorotov *et al., Nature Comm.* (2017)

Detecting magnon pumping by NV-center relaxometry







$$\Gamma_\pm \propto n(\omega_\pm)$$

$$n(\omega) \approx \frac{k_B T}{\hbar\omega - \mu}$$

Rayleigh-Jeans

SPINTRONICS

Control and local measurement of the spin chemical potential in a magnetic insulator

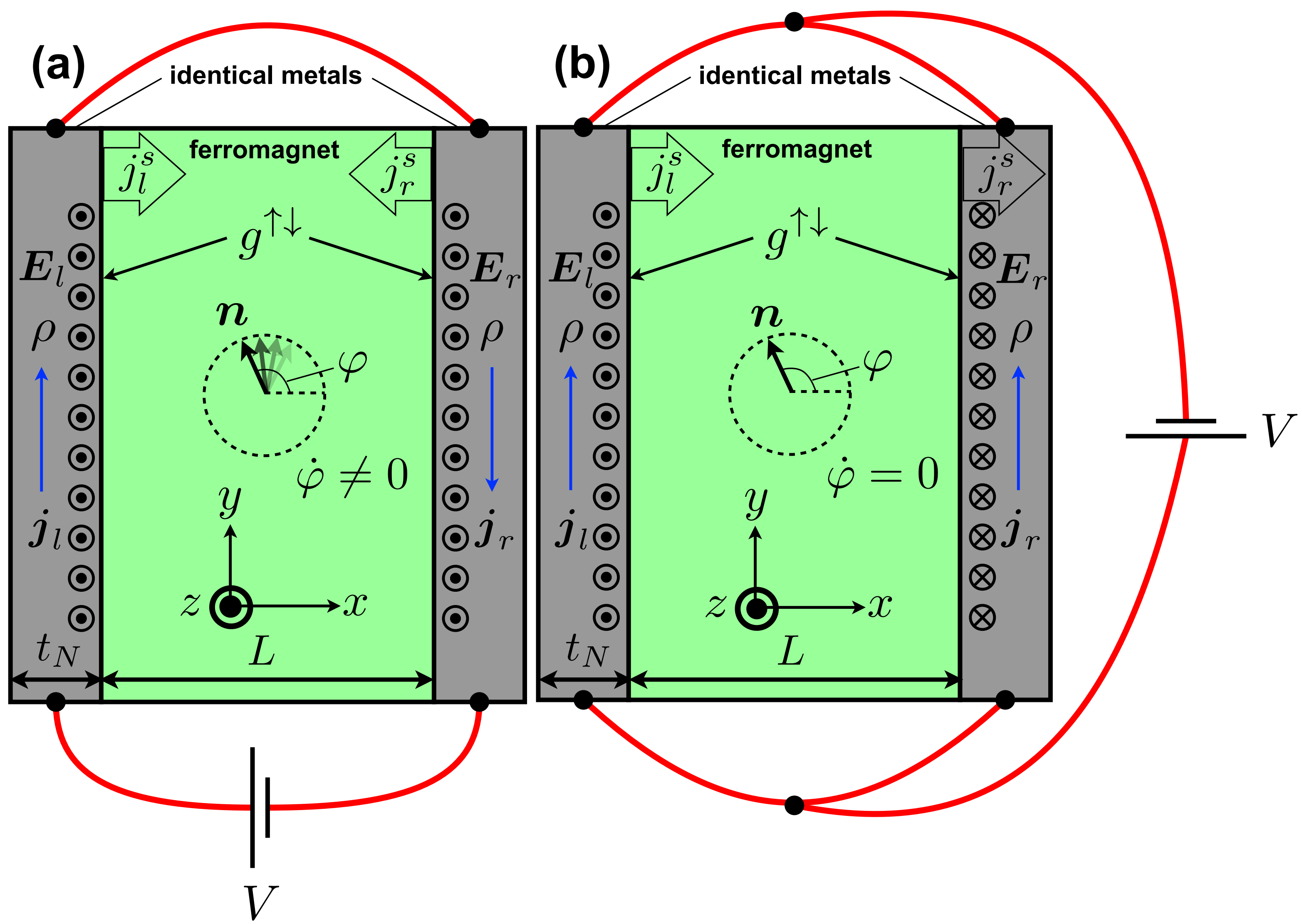
Chunhui Du,[1*] Toeno van der Sar,[1*] Tony X. Zhou,[1,2*] Pramey Upadhyaya,[3] Francesco Casola,[1,4] Huiliang Zhang,[1,4] Mehmet C. Onbasli,[5,6] Caroline A. Ross,[5] Ronald L. Walsworth,[1,4] Yaroslav Tserkovnyak,[3] Amir Yacoby[1,2]†

Du *et al.*, *Science* (2017)

Long-ranged magnetoresistance

- Circulating current through two metal films in series (a) spins the order, reducing the overall dissipation

$$\rho_m = -\frac{\vartheta^2}{g^{\uparrow\downarrow} + g_\alpha/2}$$



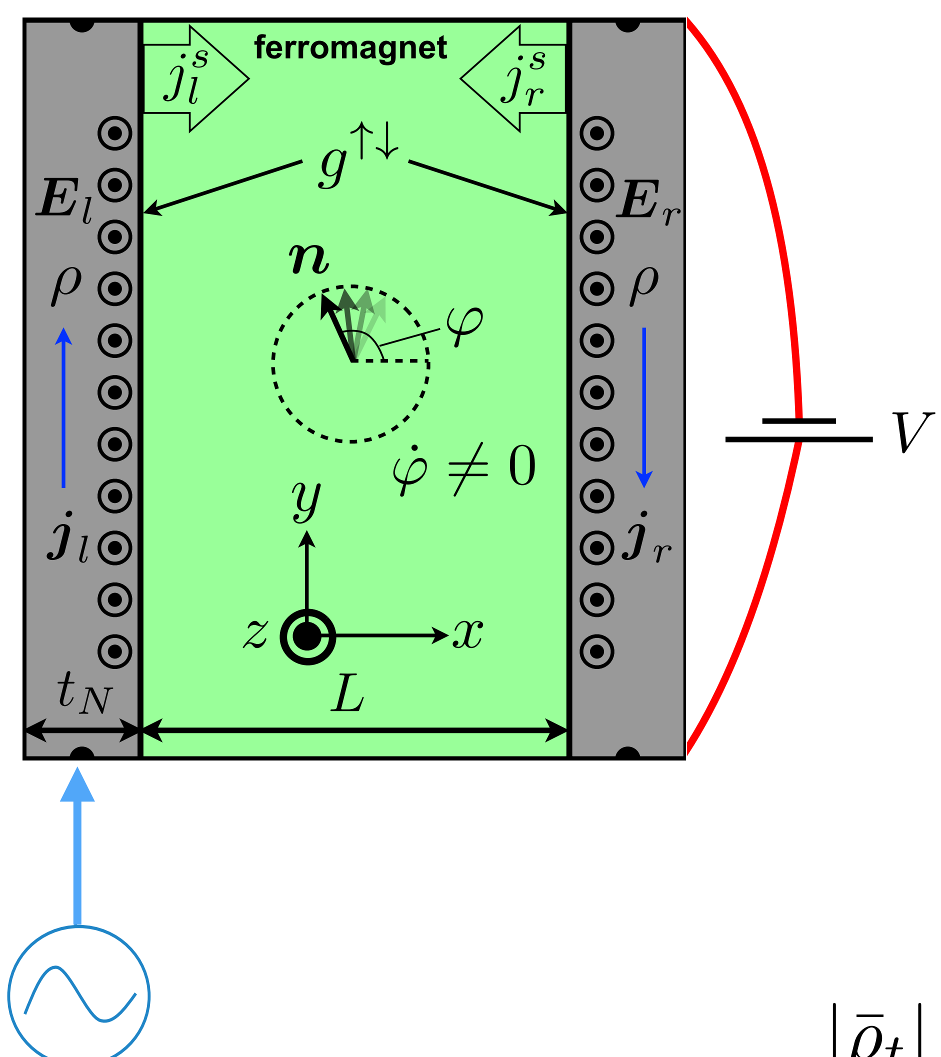
$$\rho_m = 0$$

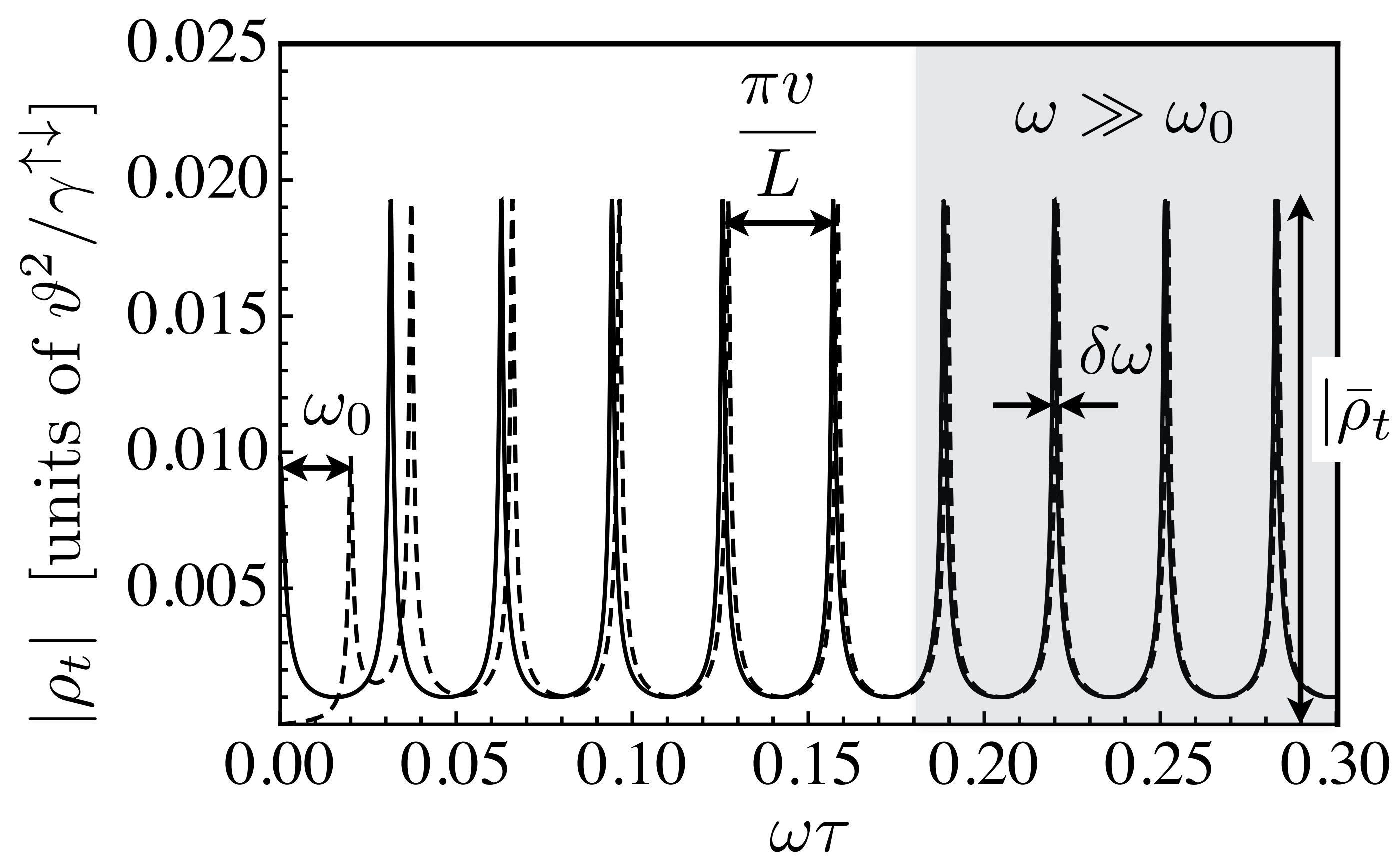
- In the parallel configuration, the torques are balanced, and the magnet remains stationary, causing more net friction

Takei and YT, *PRL* (2015)

AC transresistance

- While the DC spin supercurrent (and corresponding drag) can be quenched by an in-plane anisotropy, the AC transresistance is still fully operative on spin-wave resonances:

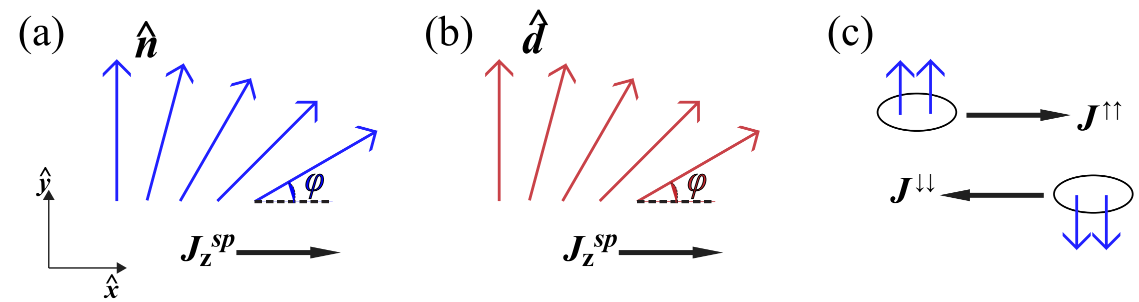


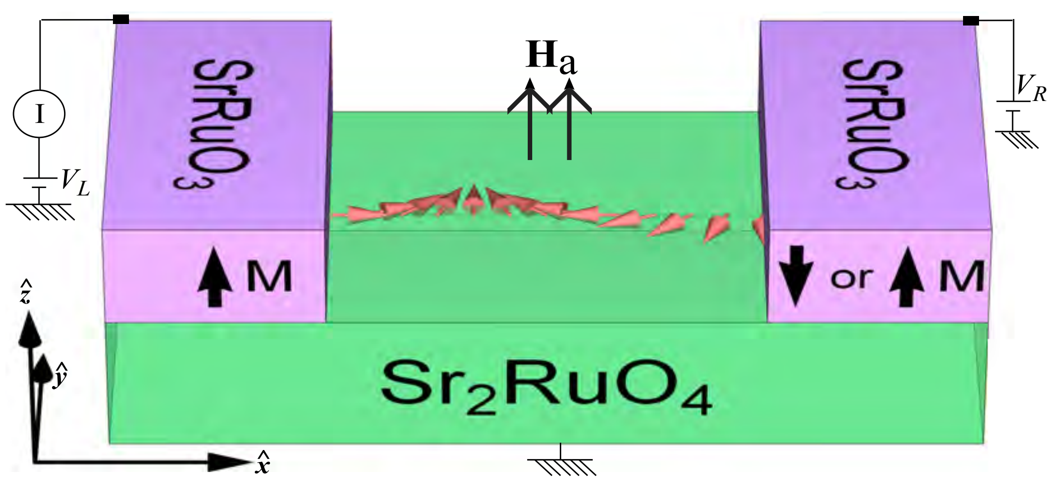


$$|\bar{\rho}_t| = \frac{\vartheta^2}{2g^{\uparrow\downarrow} + g_\alpha/2}$$

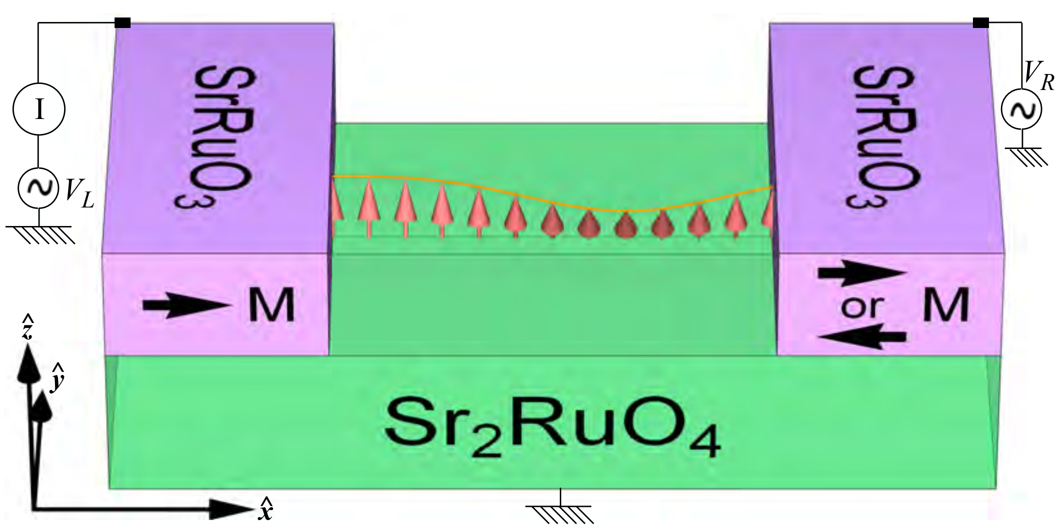
Takei and YT, *PRL* (2015)

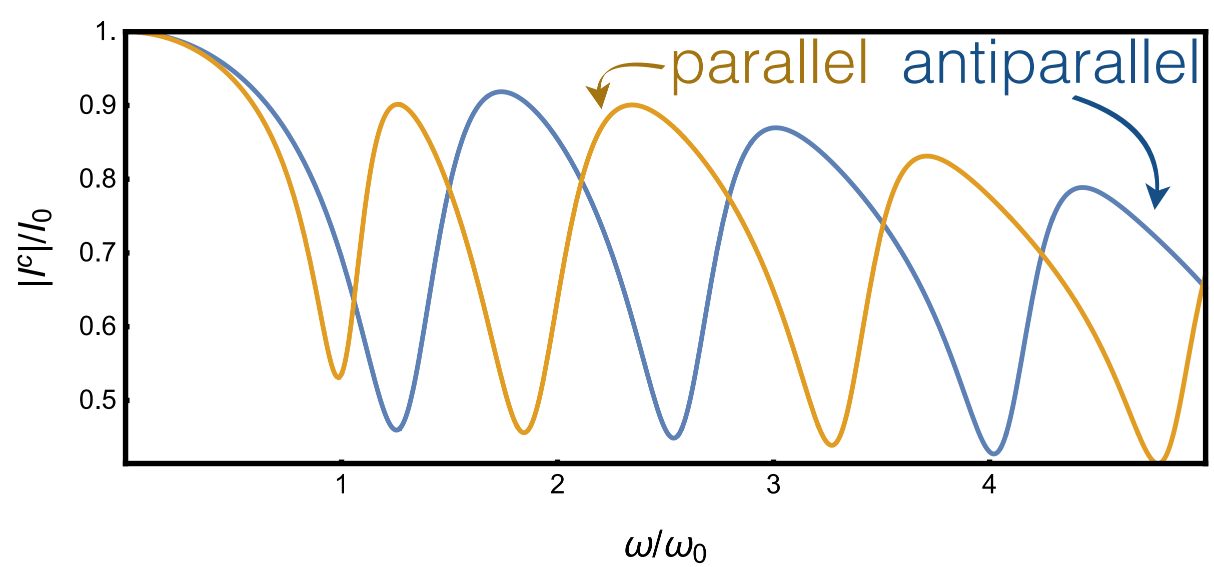
Spin-mediated transresistance of Strontium Ruthenate





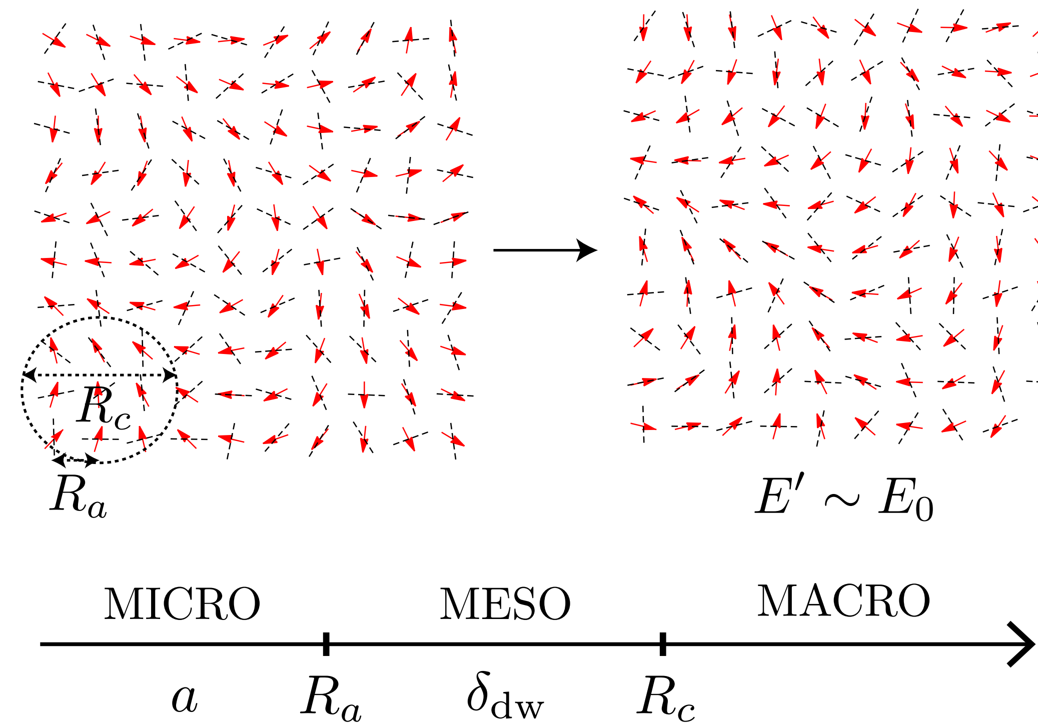
$$I^c = \sum_\sigma I^\sigma = I_0\left[1 - \frac{g_L g_R (p_L - p_R)^2}{(g_L + g_R)(g_L + g_R + g_\alpha) - (p_L g_L + p_R g_R)^2}\right]$$

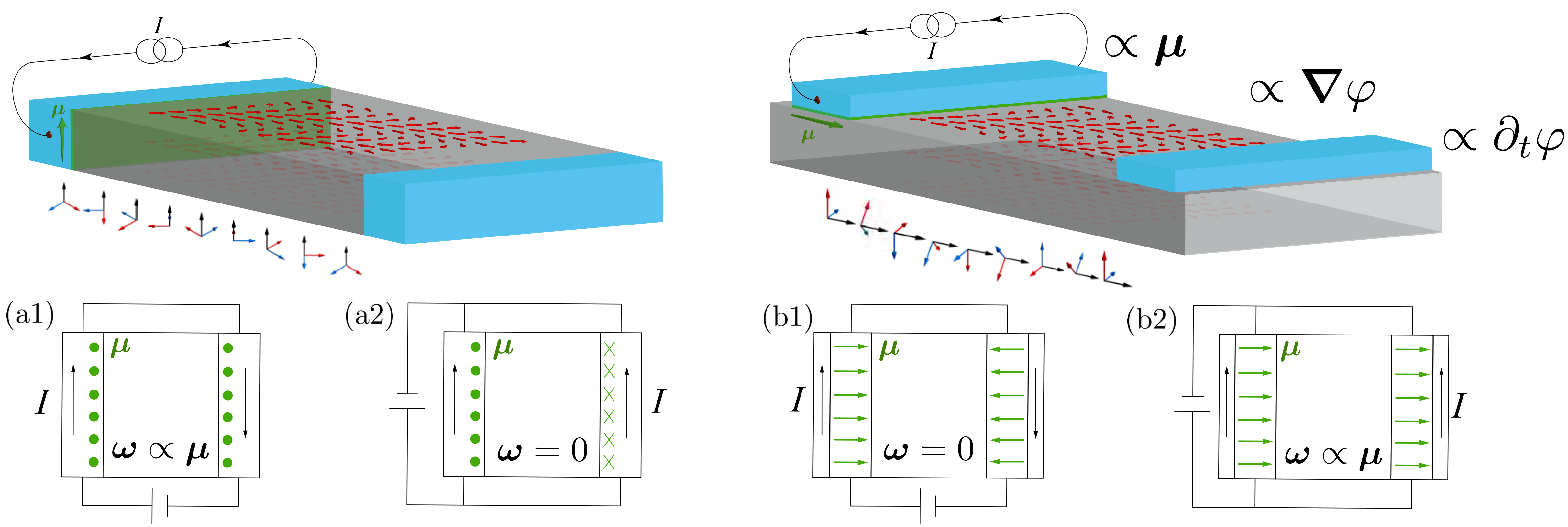




Chung, Kim, Lee, and YT, *arXiv* (2018)

“SU(2) superfluidity” in spin glasses



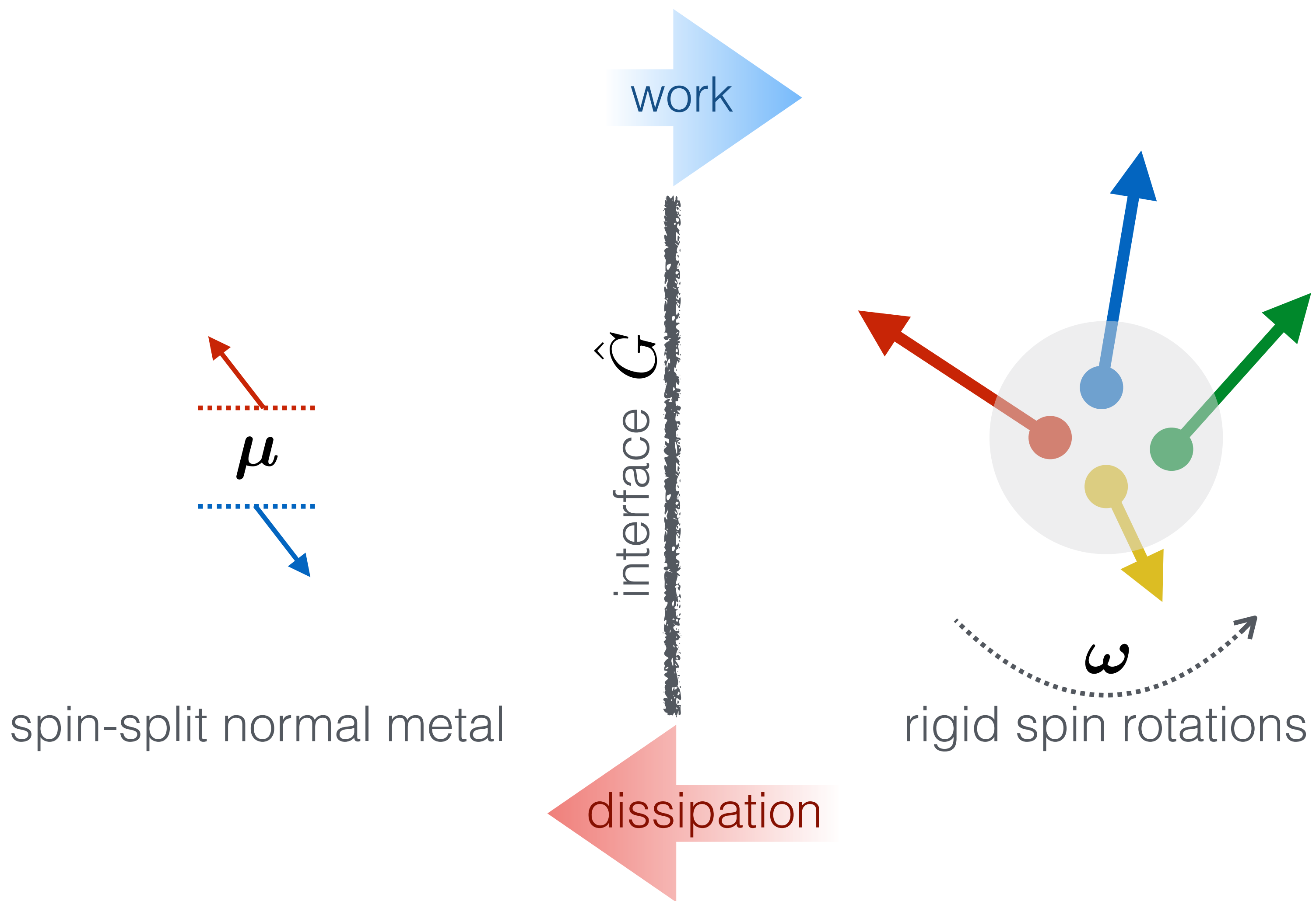


winding dynamics in the plane perpendicular to spin injection

YT and Ochoa, *PRB* (2017); Ochoa, Zarzuela, and YT, *arXiv* (2018)

Boundary energy transfer for rigid rotations

generalized spin transfer



$$R = \frac{1}{2}(\hbar\boldsymbol{\omega} - \boldsymbol{\mu})^T \hat{G}(\hbar\boldsymbol{\omega} - \boldsymbol{\mu})$$

- three independent dissipation coefficients *G*, along three principal axes

Rayleigh dissipation function ("rotational viscosity")

YT and Ochoa, *PRB* (2017)

Take-home messages

- Coherent (spin) order-parameter textures as solid-state transport medium
- Hydrodynamics that is rooted in the winding topology
- Thermoelectric and quantum means to pump and couple to the condensate
- Engineering microwave "cavities" based on exchange-dominated dynamics

Thank you!