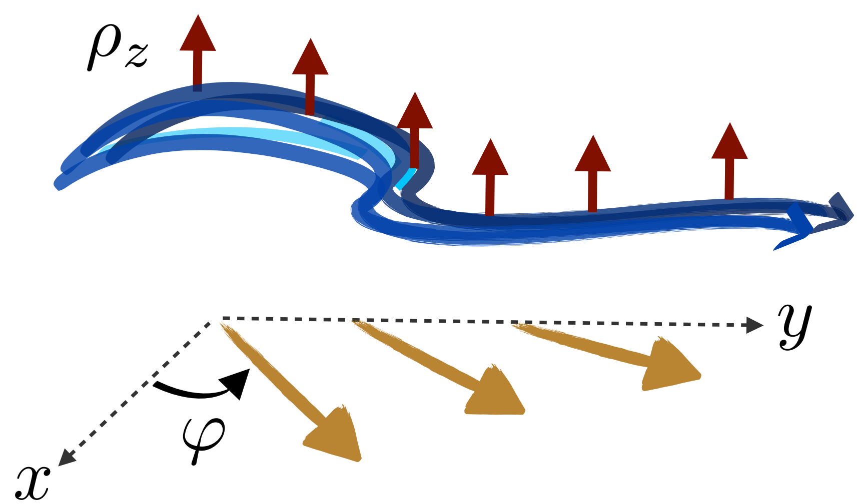
Spin condensation and superfluidity in insulators

(a tale of two flows in magnetic insulators, and their interconversions)



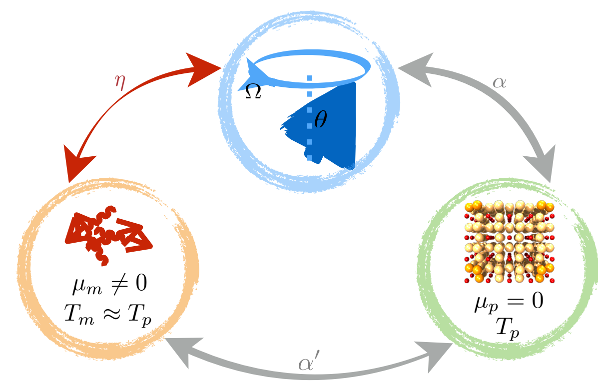
$$\mathbf{j}_{\mathrm{th}} \propto \boldsymbol{\nabla} T, \boldsymbol{\nabla} \mu$$
$$\mathbf{j}_c \propto \boldsymbol{\nabla} \varphi$$

Yaroslav Tserkovnyak
UCLA

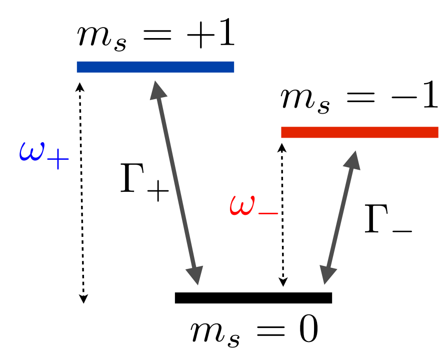
in collaboration with Scott Bender (UCLA → Utrecht), Benedetta Flebus (Utrecht → UCLA), Pramey Upadhyaya (UCLA), Rembert Duine (Utrecht), Ilya Krivorotov (UC Irvine), and Amir Yacoby (Harvard)

Outline

- *Two-fluid* (coherent vs incoherent) view on collective magnetic dynamics

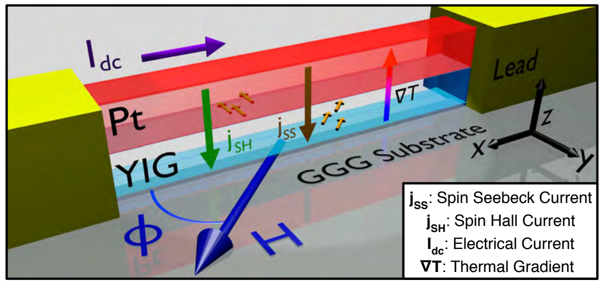


- NV-center measurement and coherent control of *magnon chemical potential*



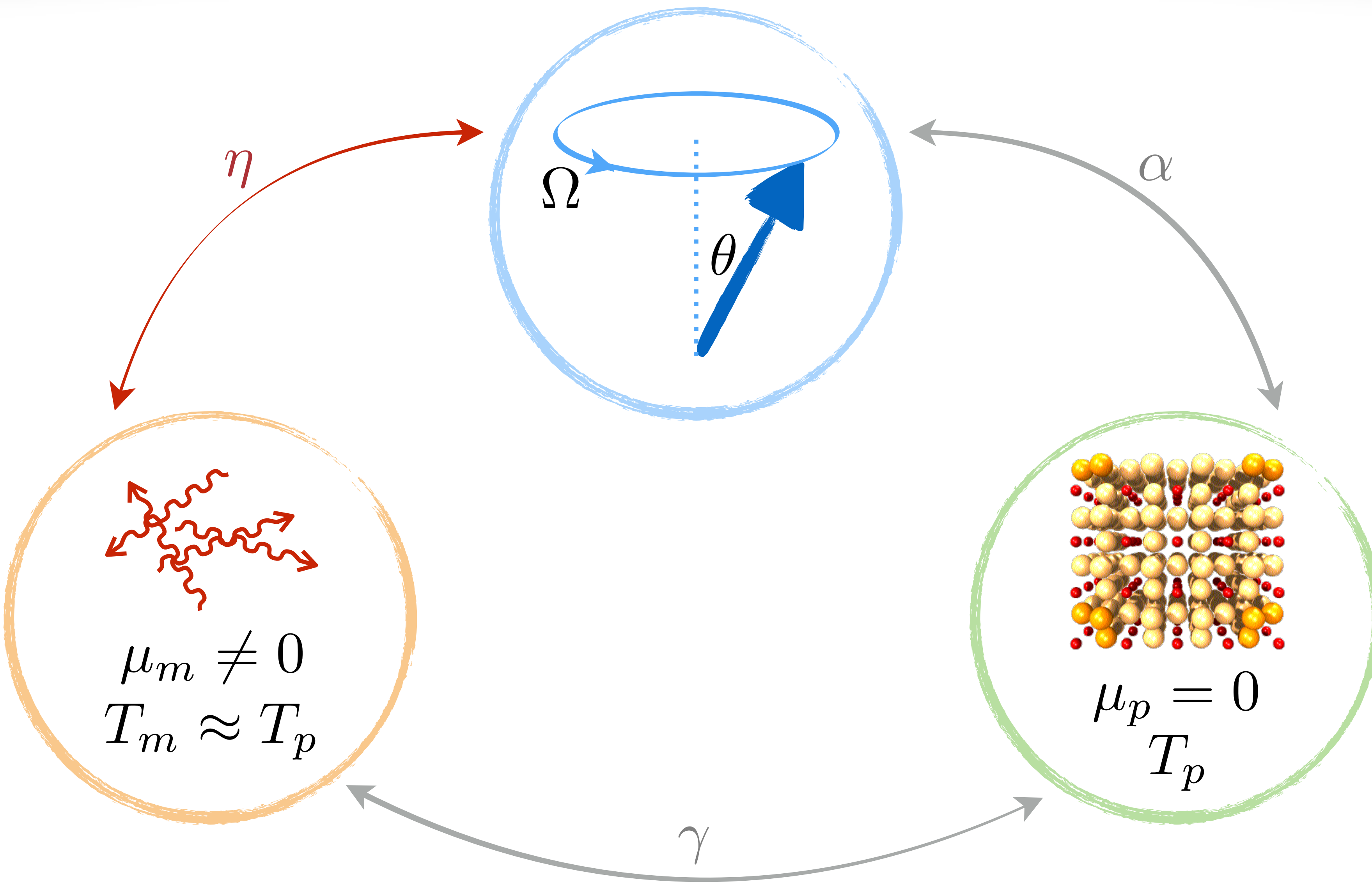
Exp: **Amir Yacoby** (Harvard)

- Thermoelectrically-pumped *magnon condensation*



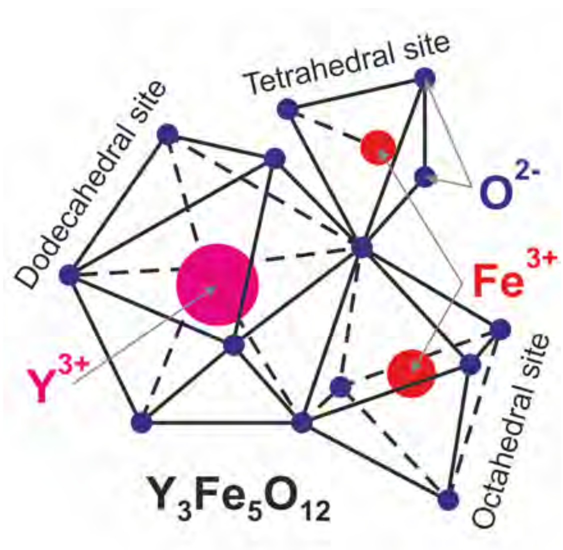
Exp: **Ilya Krivorotov** (UC Irvine)

General view

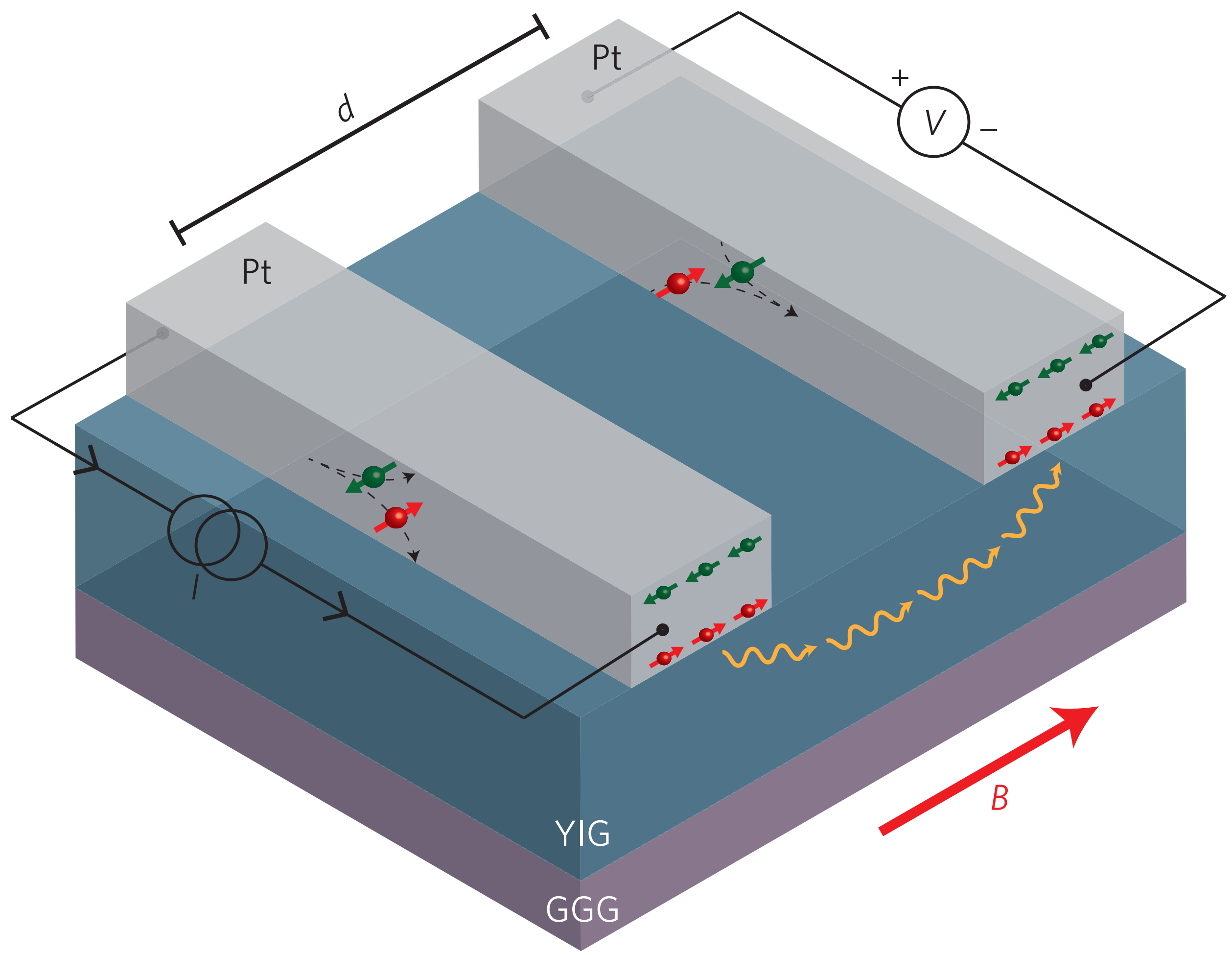


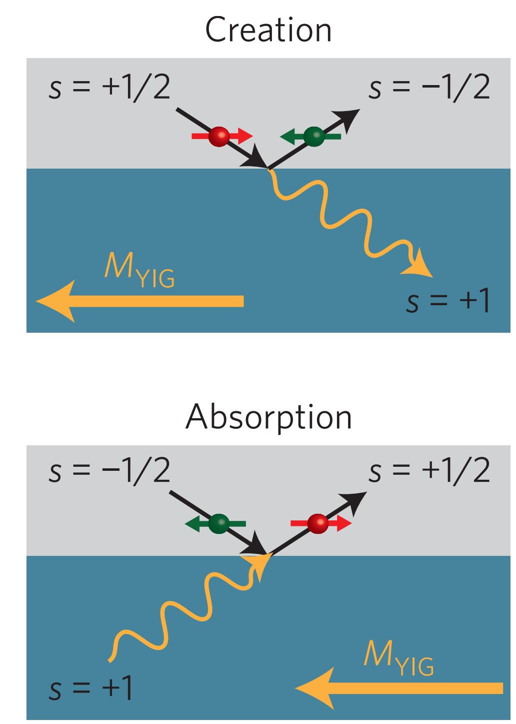
- Phonons equilibrate fast and define a thermalizing environment
- Incoherent (thermal) magnons form a quasiequilibrium ensemble, with well-defined chemical potential and temperature
- As spin-orbit interactions are weak compared to exchange, magnon chemical potential can depart significantly from the equilibrium (zero) value

Long-ranged magnon transport



(YIG)





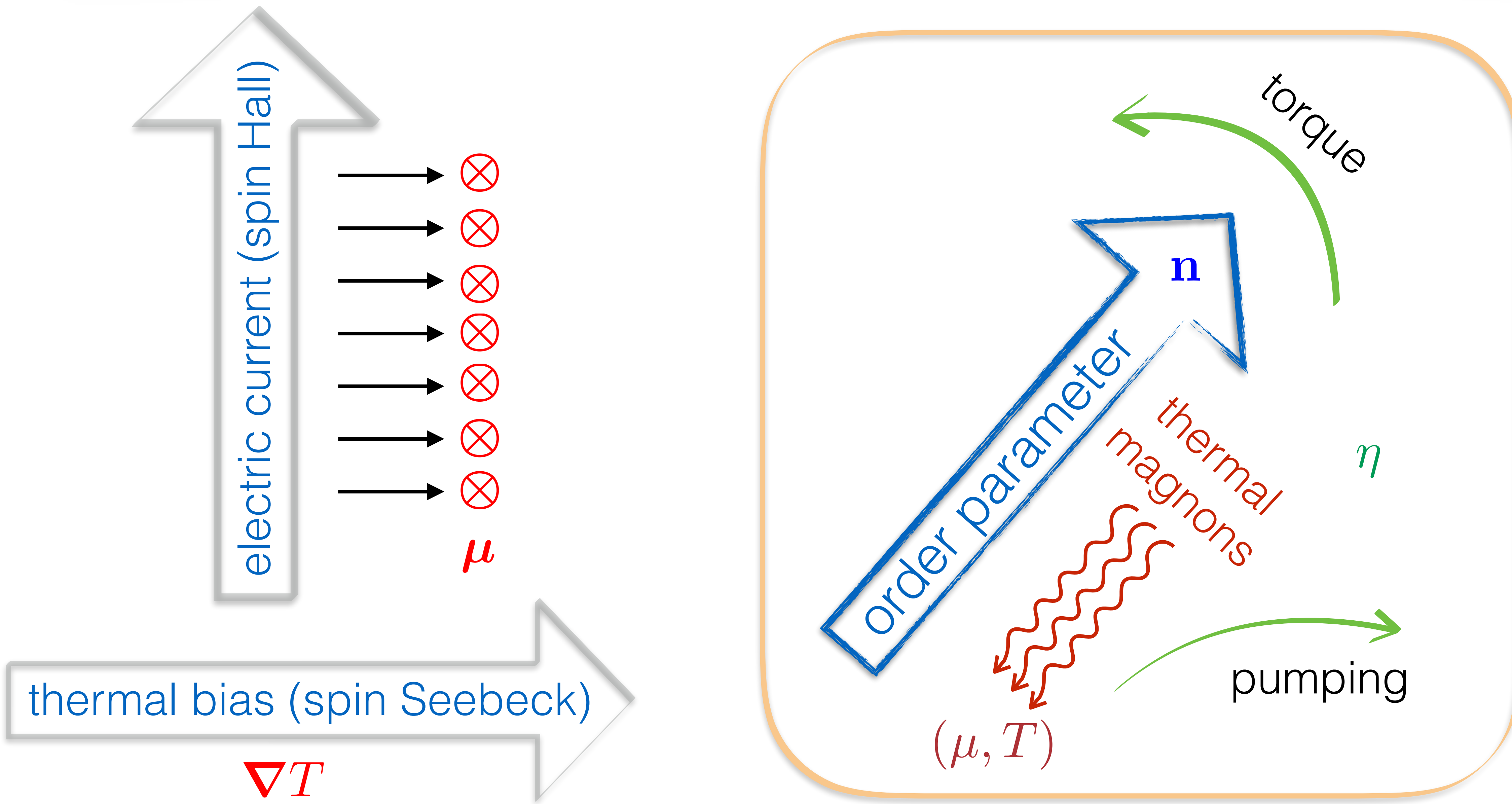
spin Hall (and spin Seebeck) injection and detection of spin flow in an insulator

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

→ *condensation of magnons and superfluid phenomena?*

(dynamic instability of the static uniform background)

Thermal-magnons/order-parameter coupling η



- Coherent order-parameter dynamics experiences magnonic torque $\propto \mu$
- Magnon pumping $\propto \dot{\mathbf{n}}$
- According to the Onsager reciprocity, the same proportionality coefficient η

Symmetry-based phenomenology

Directional order-parameter dynamics:

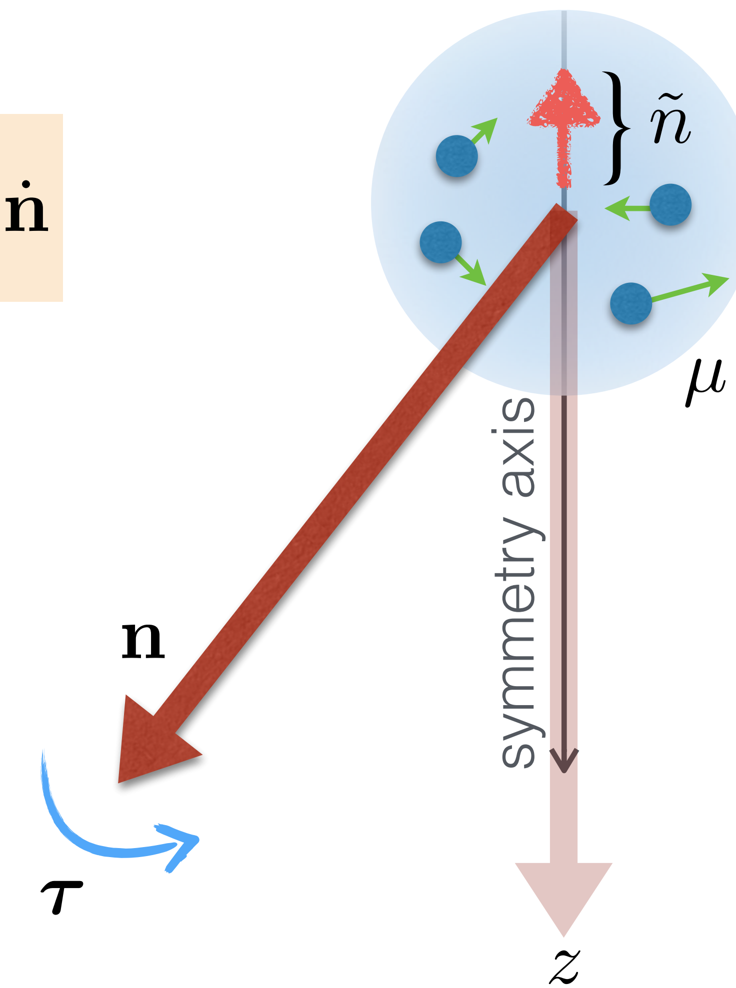
$$\hbar\dot{\mathbf{n}} = \overbrace{-\eta n_z \mathbf{n} \times (\hbar n_z \dot{\mathbf{n}} - \mu \mathbf{n} \times \hat{\mathbf{z}})}^{\boldsymbol{\tau}} + \frac{1}{s}\mathbf{n} \times \mathbf{H} - \alpha\hbar\mathbf{n} \times \dot{\mathbf{n}}$$

damping torque LLG

Thermal-magnon transport:

$$\dot{\tilde{n}} = -\eta \frac{s}{\hbar} \hat{\mathbf{z}} \cdot \mathbf{n} \times (\hbar n_z \dot{\mathbf{n}} - \mu \mathbf{n} \times \hat{\mathbf{z}}) - \boldsymbol{\nabla} \cdot \tilde{\mathbf{j}} - \gamma\mu$$

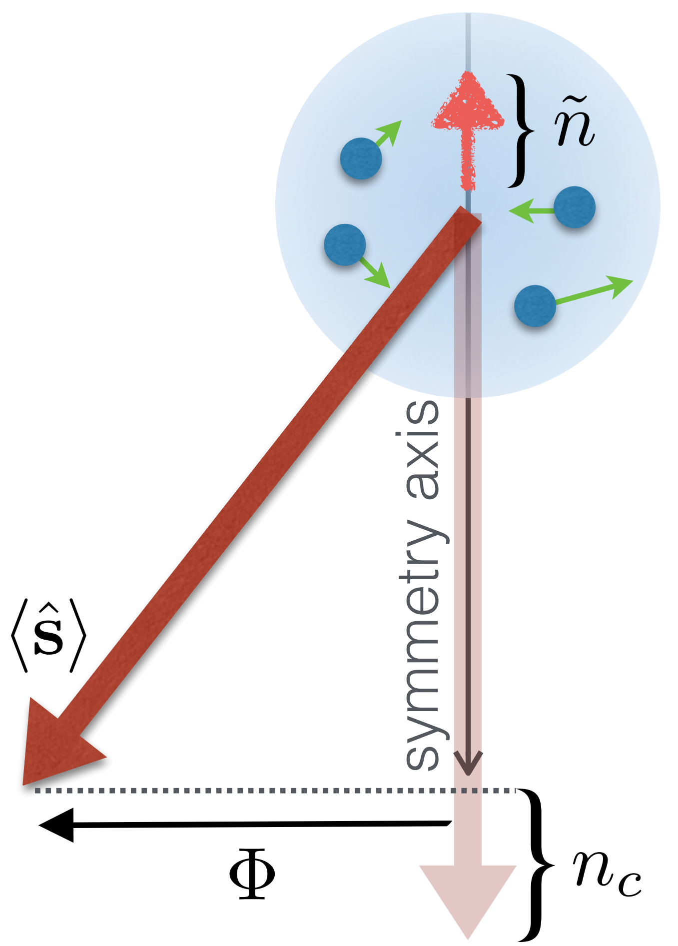
pumping relaxation diffusion



- Formation of heat-driven magnon condensates and the ensuing spin dynamics
- Normal-superfluid interconversion in the coupled flow of spin and heat

Flebus, Upadhyaya, Duine, and YT, *PRB* (2016)

Thermomagnonic self-torques: Microscopics



Holstein-Primakoff transformation:

$\hat{s}_x - i\hat{s}_y \approx \sqrt{2s}\hat{\Phi}$ and $\hat{s}_z = \hat{\Phi}^\dagger\hat{\Phi} - s \rightarrow n_c + \tilde{n} - s$

$\hat{\Phi} = \langle\hat{\Phi}\rangle + \hat{\phi}$ — bosonic field

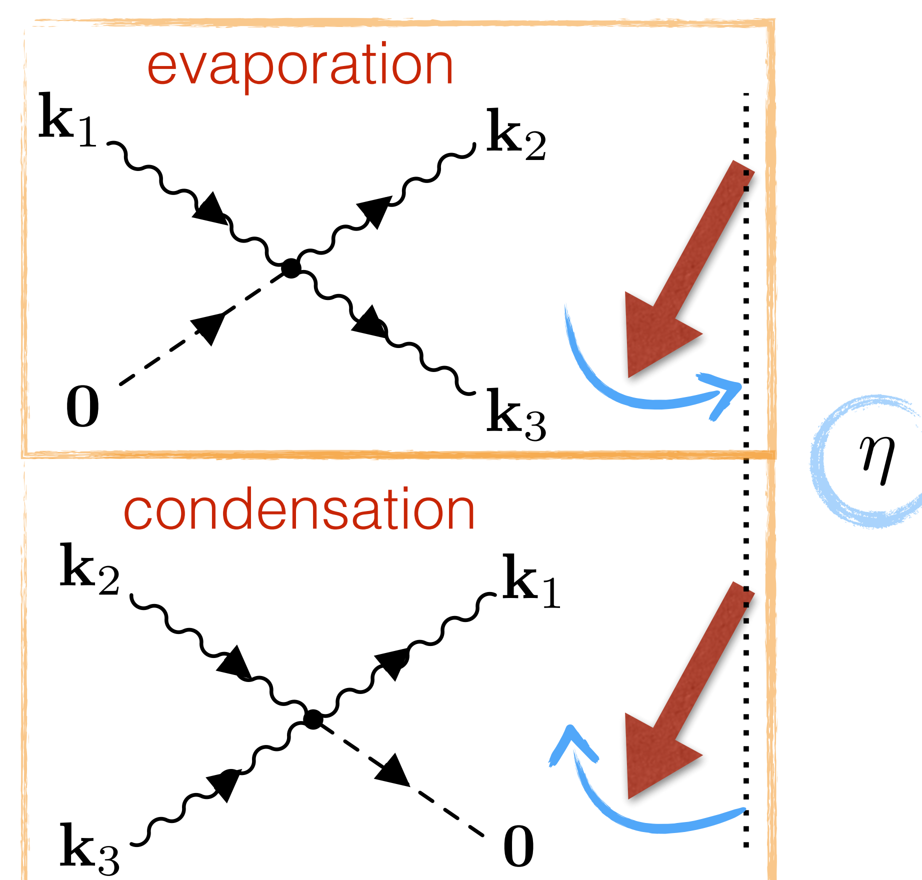
$\Phi \equiv \langle\hat{\Phi}\rangle = \sqrt{n_c}e^{-i\varphi}$ — condensate component

$\tilde{n} \equiv \langle\hat{\phi}^\dagger\hat{\phi}\rangle$ — thermal cloud

magnon-magnon interaction due to anisotropy:

$$U_{mm} \sim K\hat{\Phi}^\dagger\hat{\Phi}^\dagger\hat{\Phi}\hat{\Phi} \rightarrow K\hat{\phi}^\dagger\hat{\phi}^\dagger\hat{\phi}\Phi + \mathrm{H.c.}$$

condensate damping

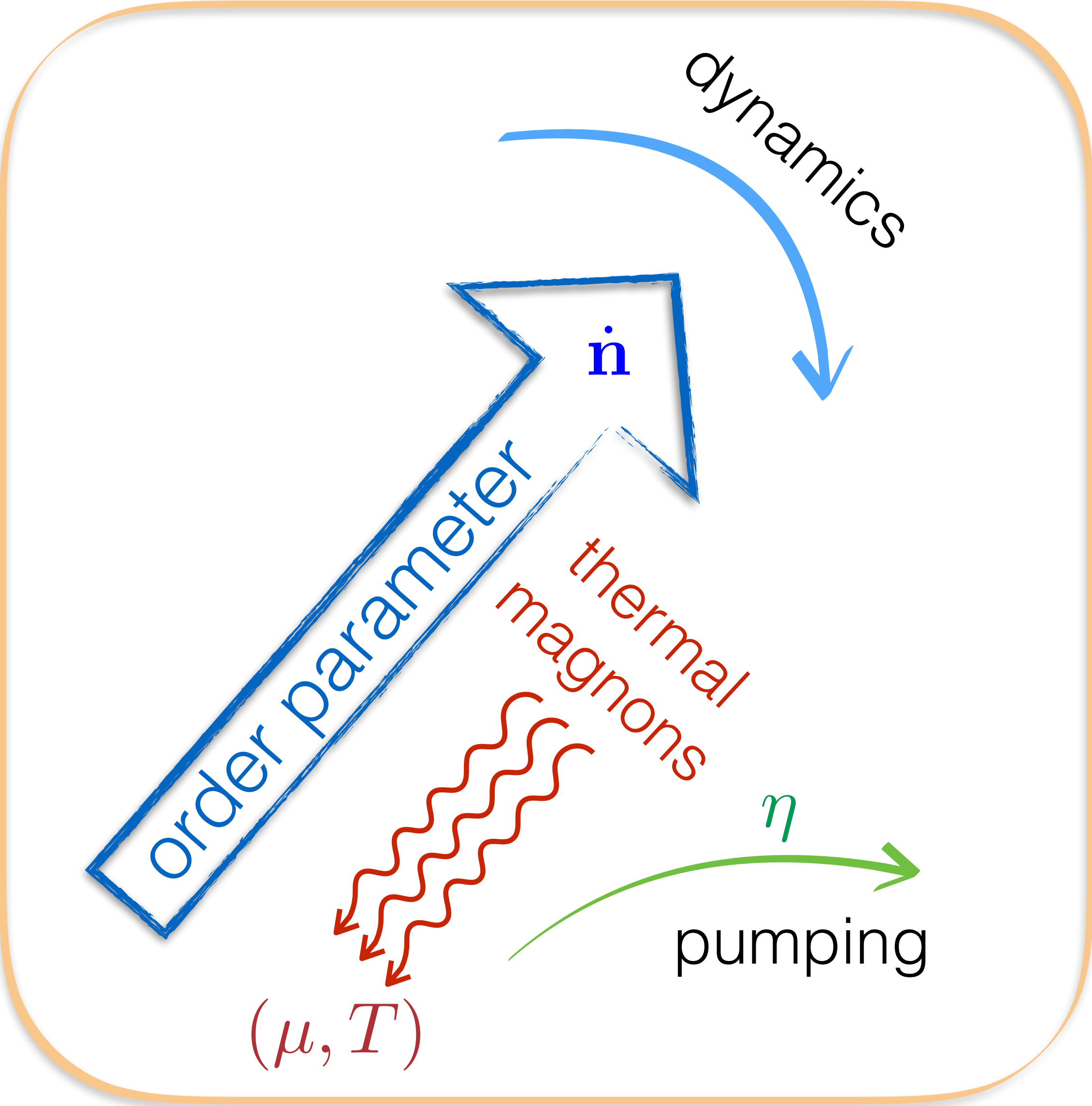


evaporation

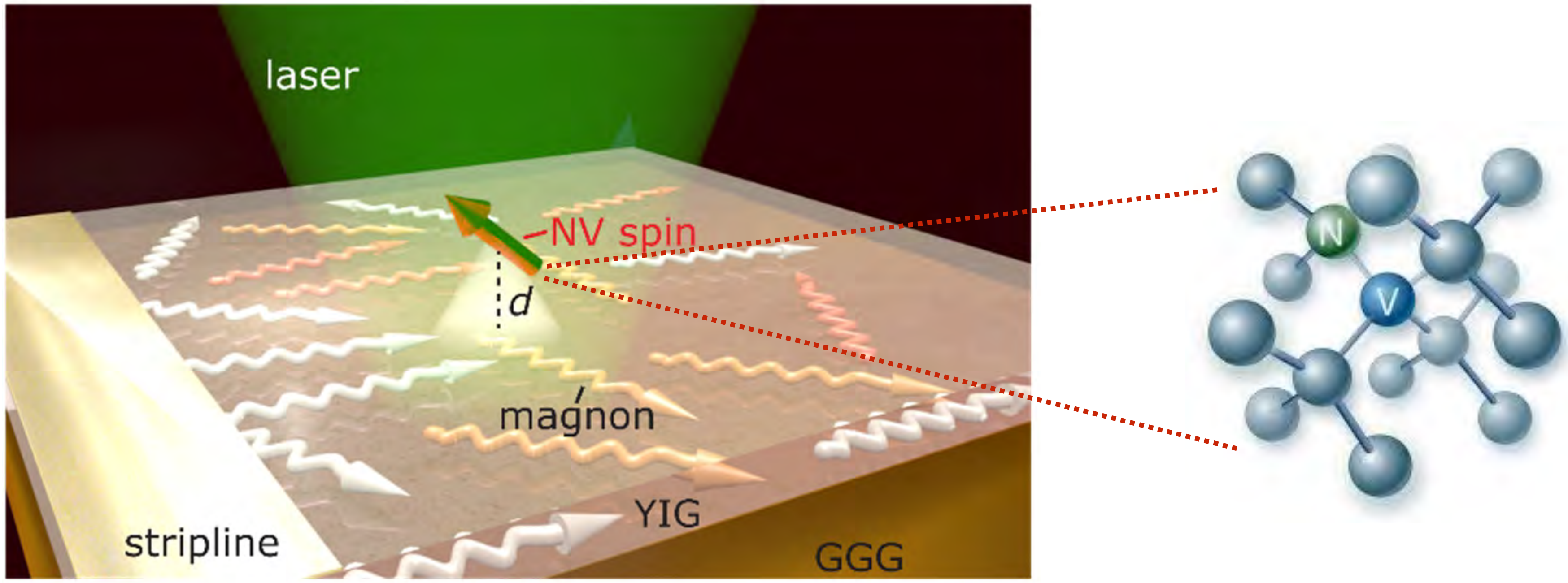
magnon pumping

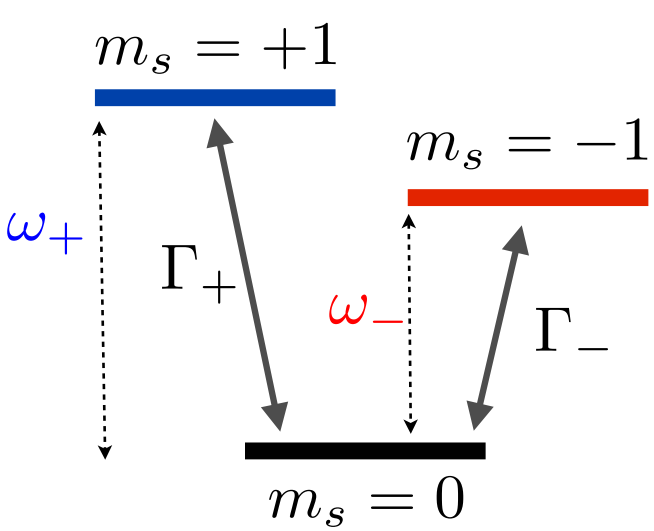
Flebus, Bender, YT, and Duine, *PRL* (2016); Bender and YT, *PRB* (2016)

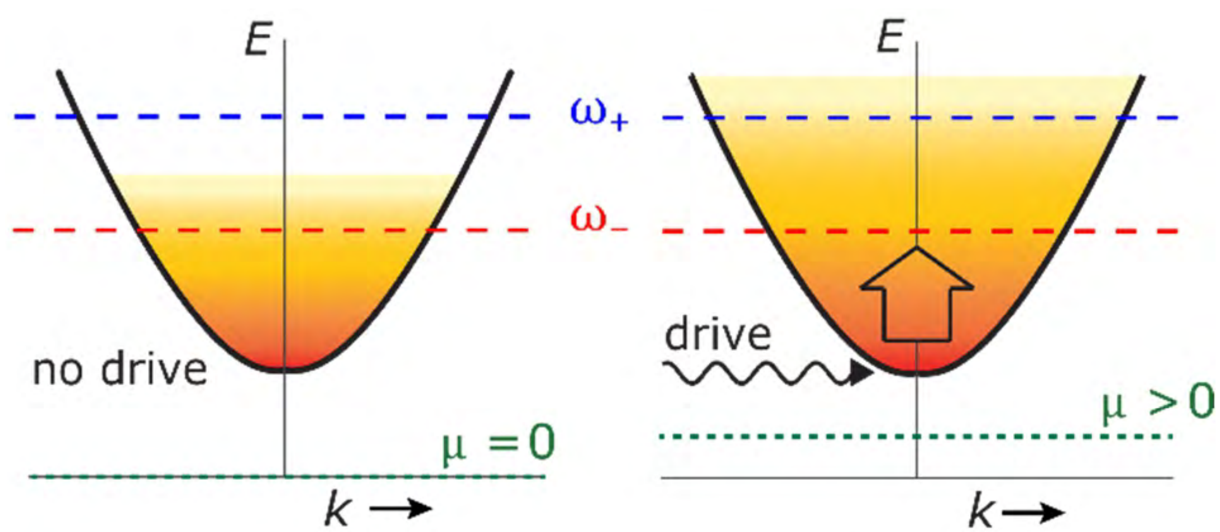
Revealing the two-fluid coupling via magnon pumping



Detecting magnon pumping by NV centers







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

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

Rayleigh-Jeans

SPINTRONICS

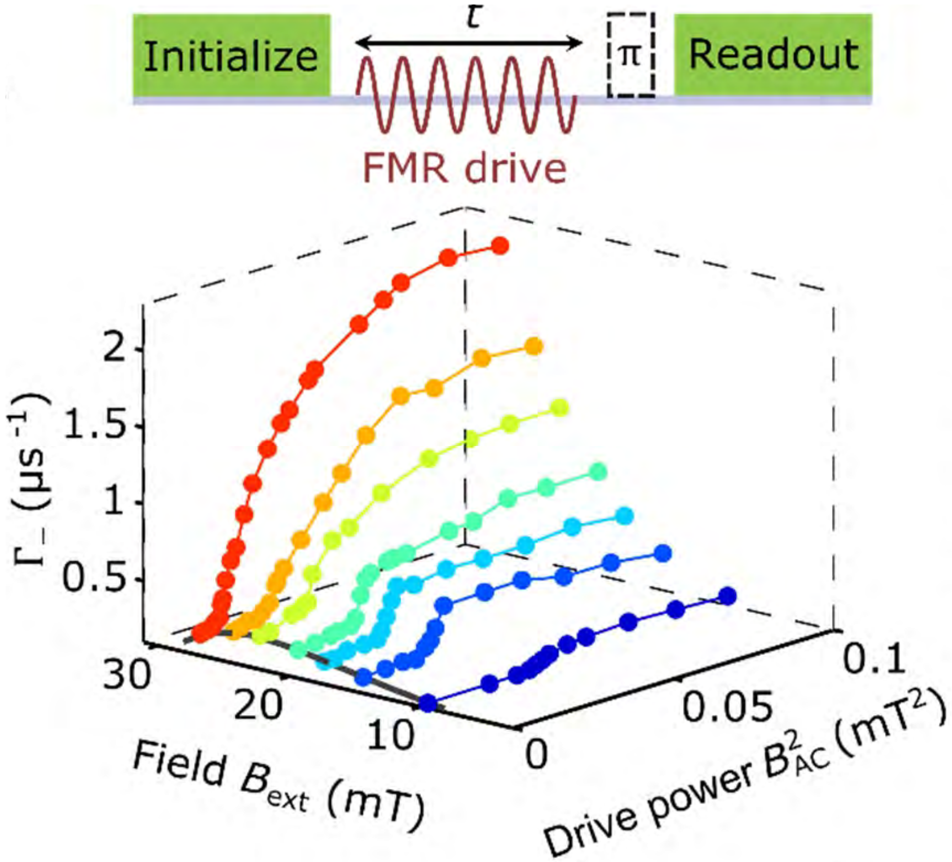
Control and local measurement of the spin chemical potential in a magnetic insulator

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]†

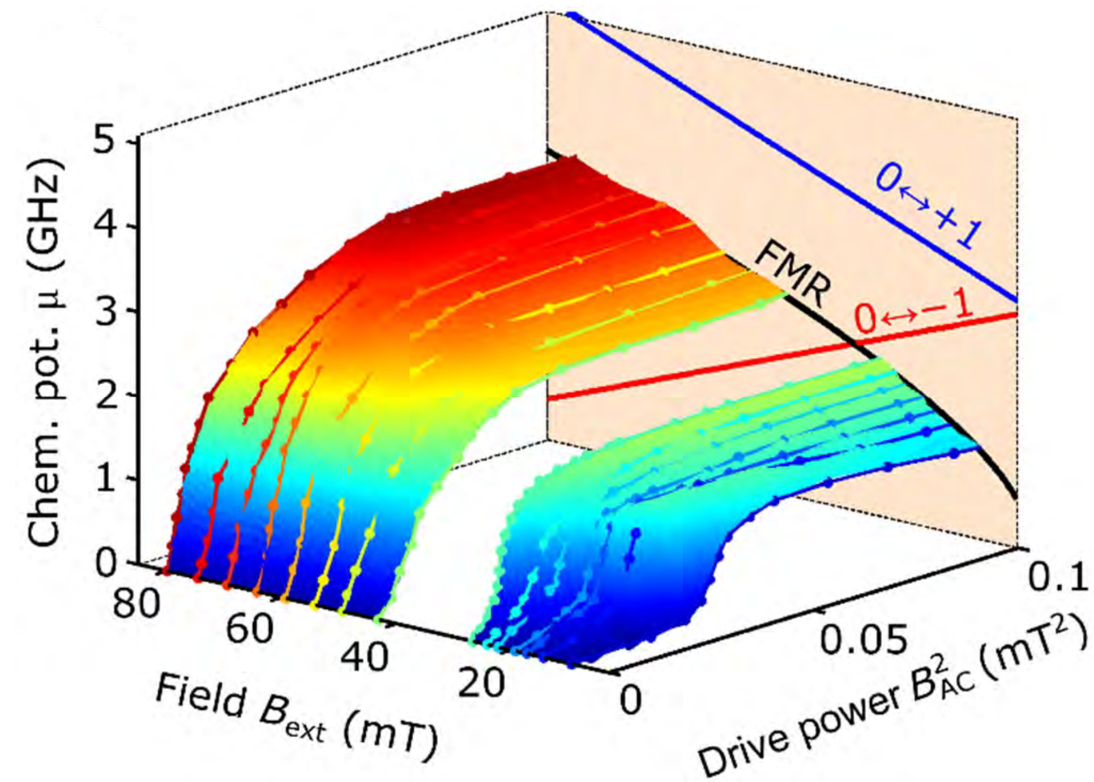
Du *et al.*, *Science* (2017)

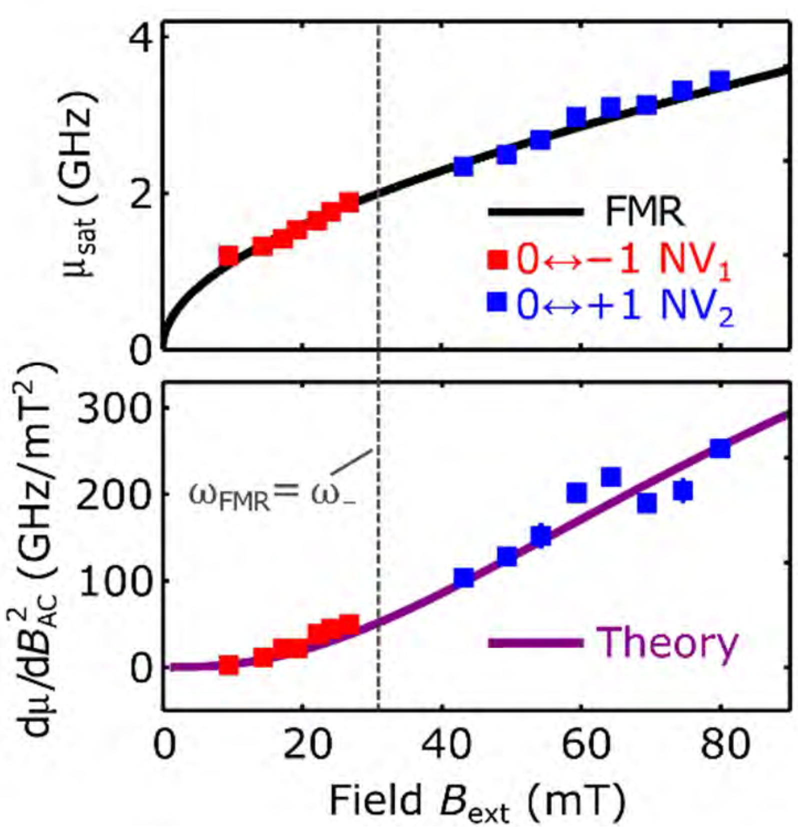
Measuring chemical potential and extracting η

NV relaxometry



$$\frac{\mu}{\hbar\omega_\pm} = 1 - \frac{\Gamma^0_\pm}{\Gamma^{ac}_\pm}$$

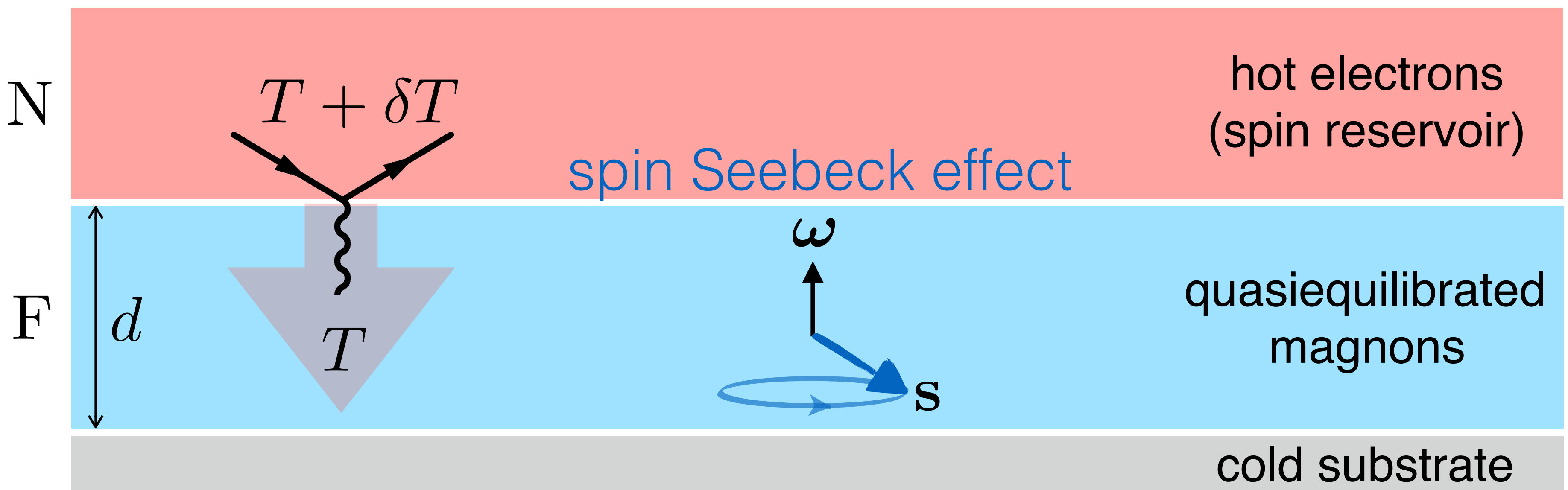


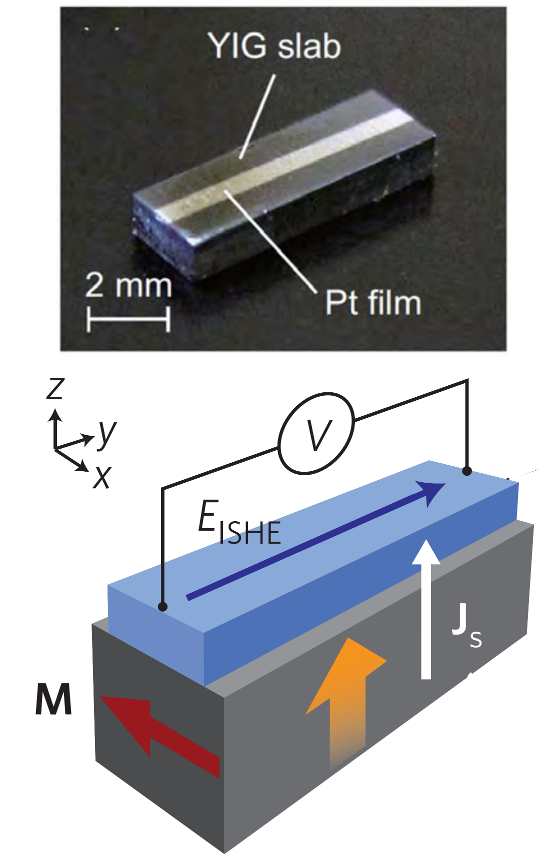


Kittel formula

extract η

Magnon BEC in thin films





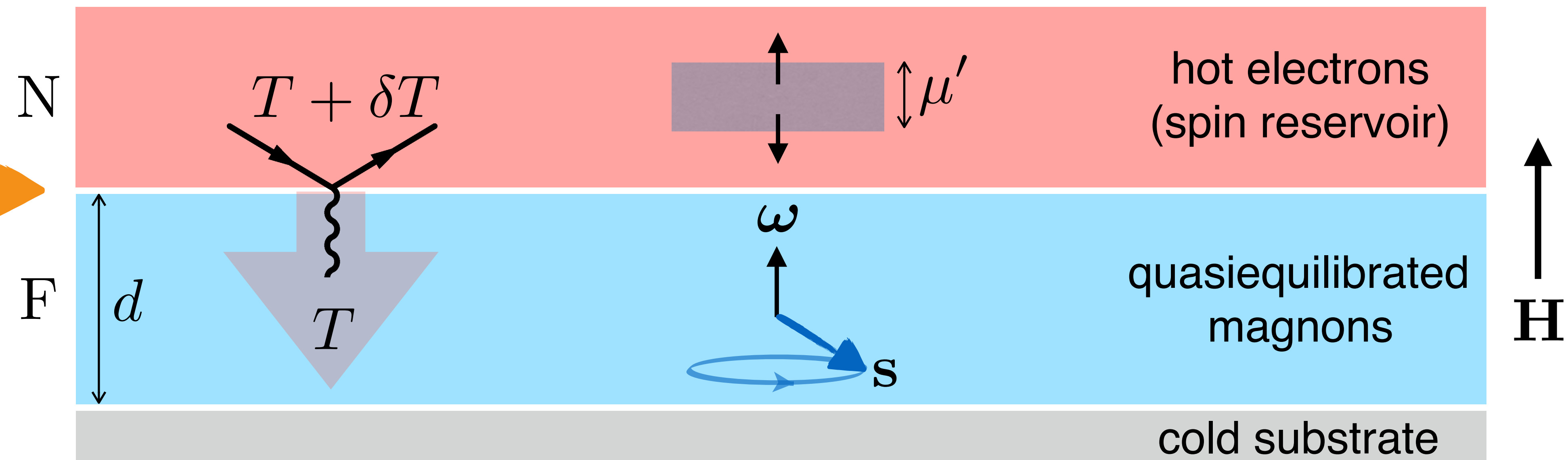
Uchida, Saitoh *et al.*, *Nature* (2008), *APL* (2010)

- 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

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

Electron/magnon-torque instabilities

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



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

electrically controlled

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

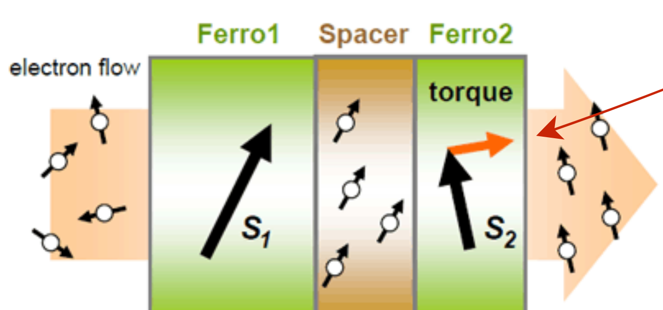
electronic torques

Gilbert damping

thermally controlled

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

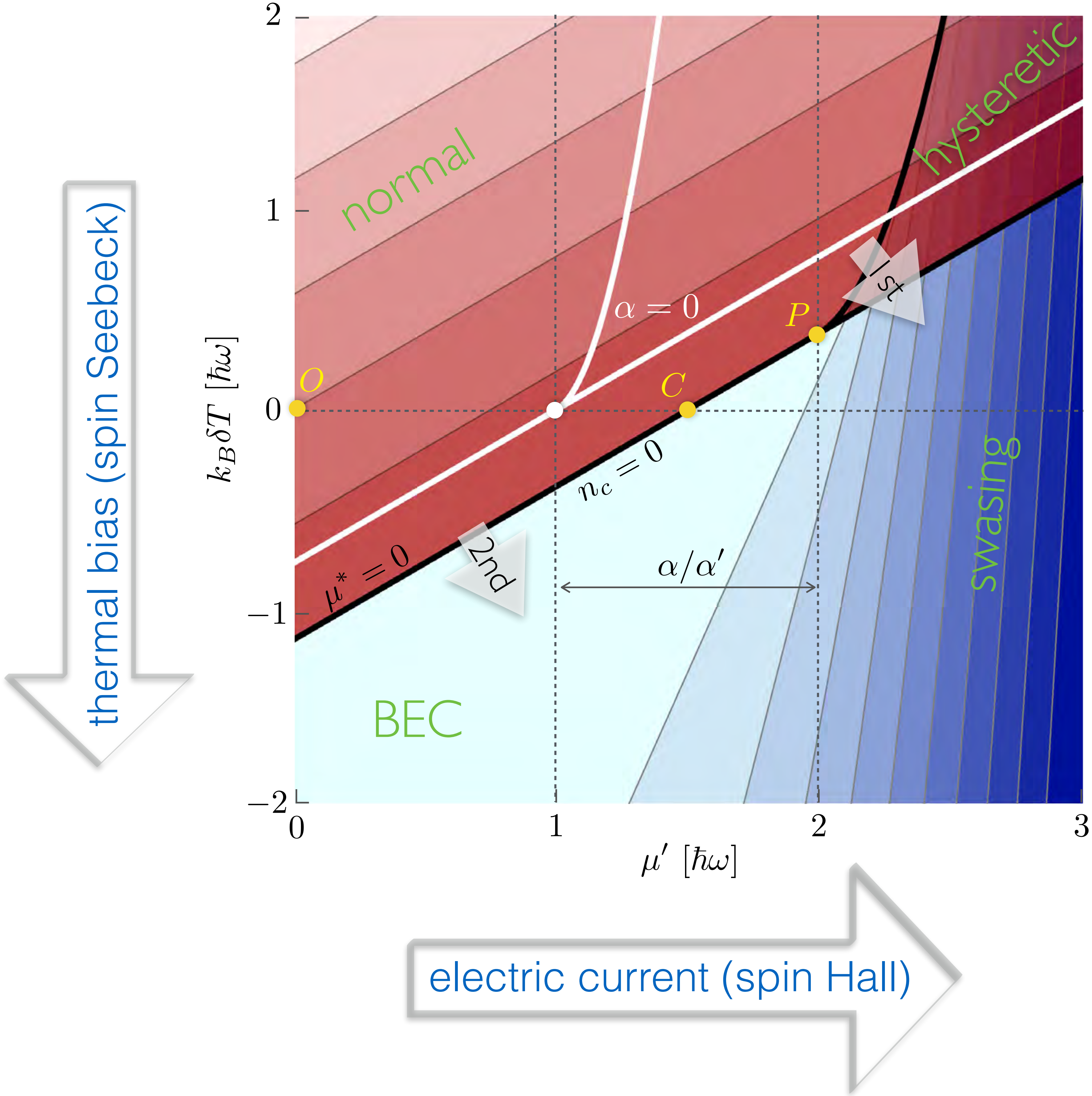
magnonic torques



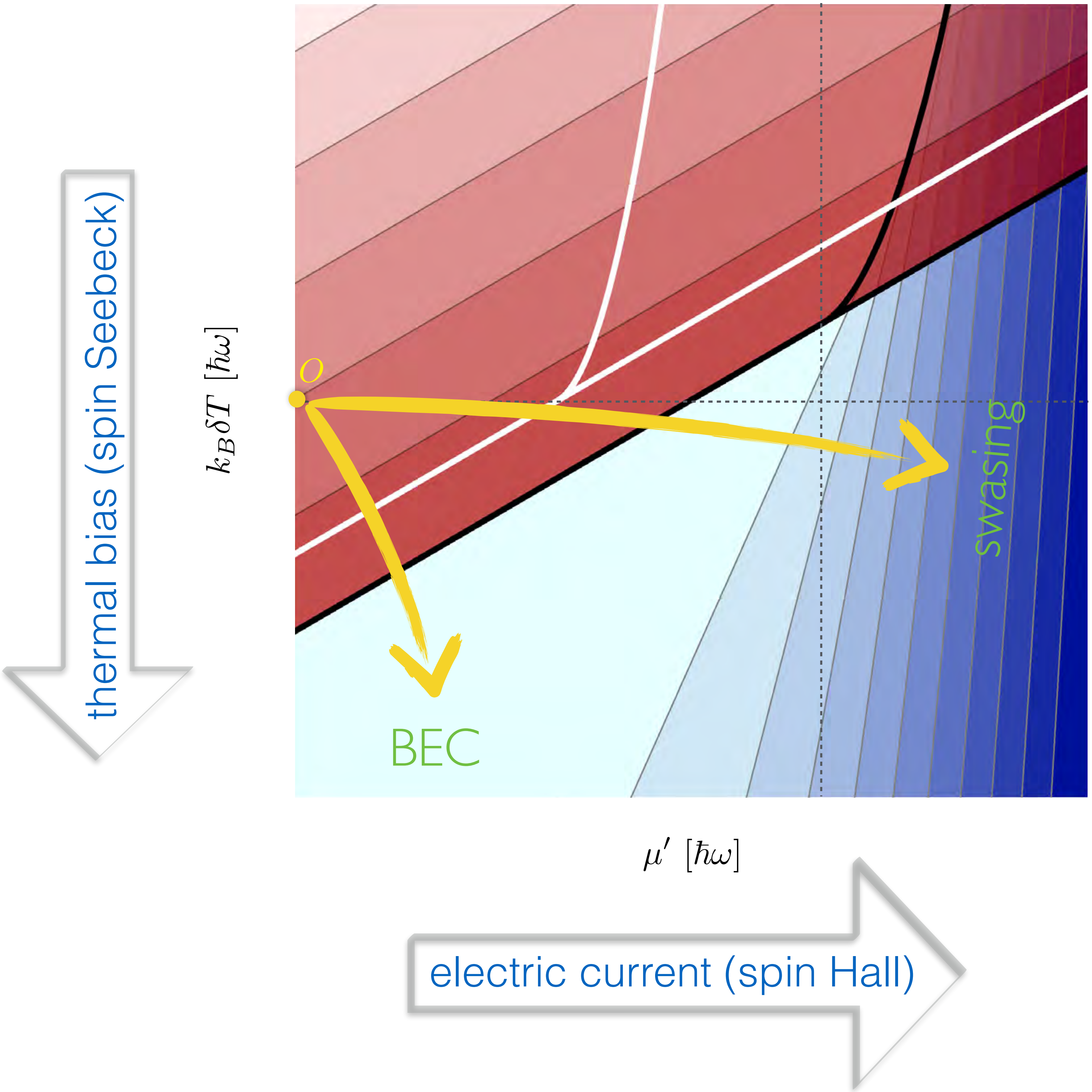
Mizukami Lab

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

Dynamic phase diagram

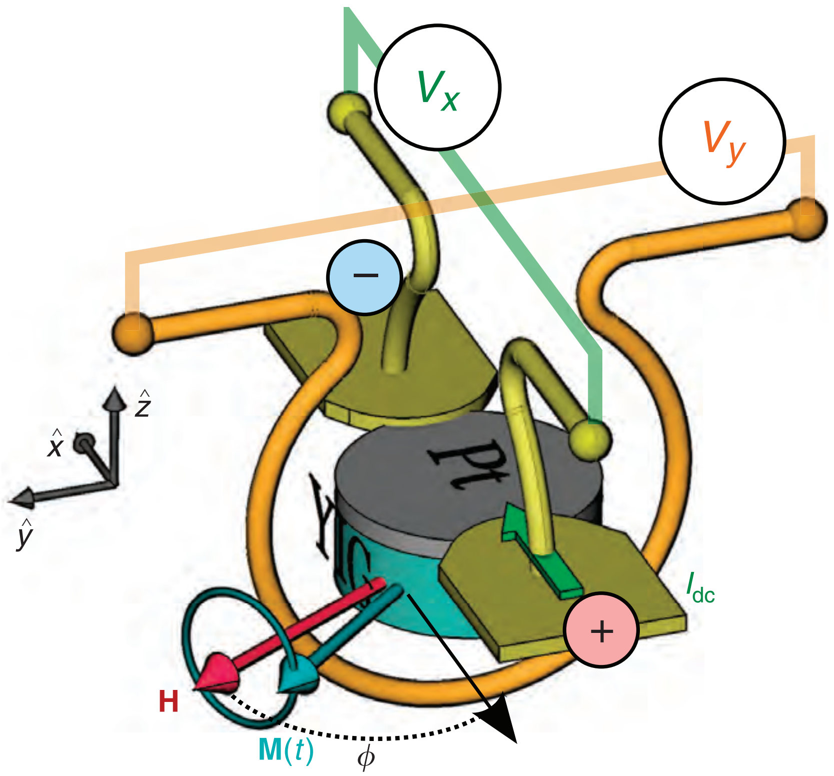


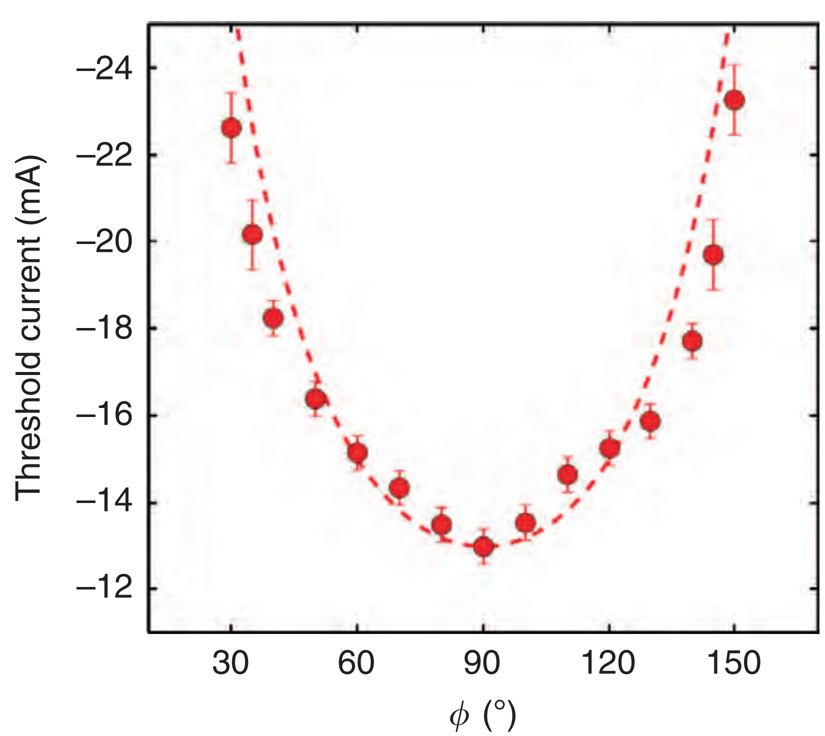
Two routes towards magnon condensates



Spin-torque nano-oscillators

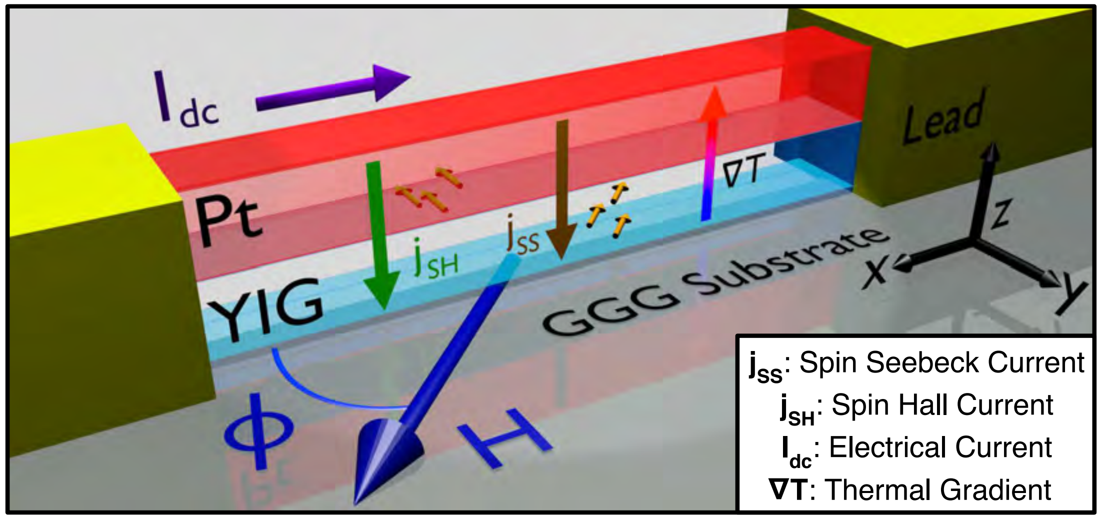
spin Hall pump:

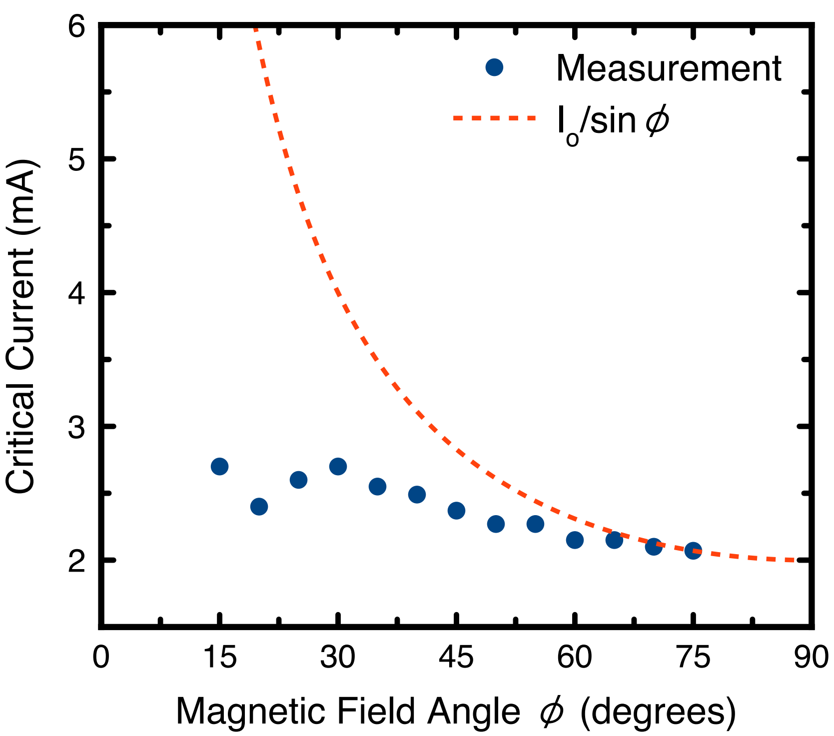




Collet, Demokritov, Klein *et al., Nature Comm.* (2016)

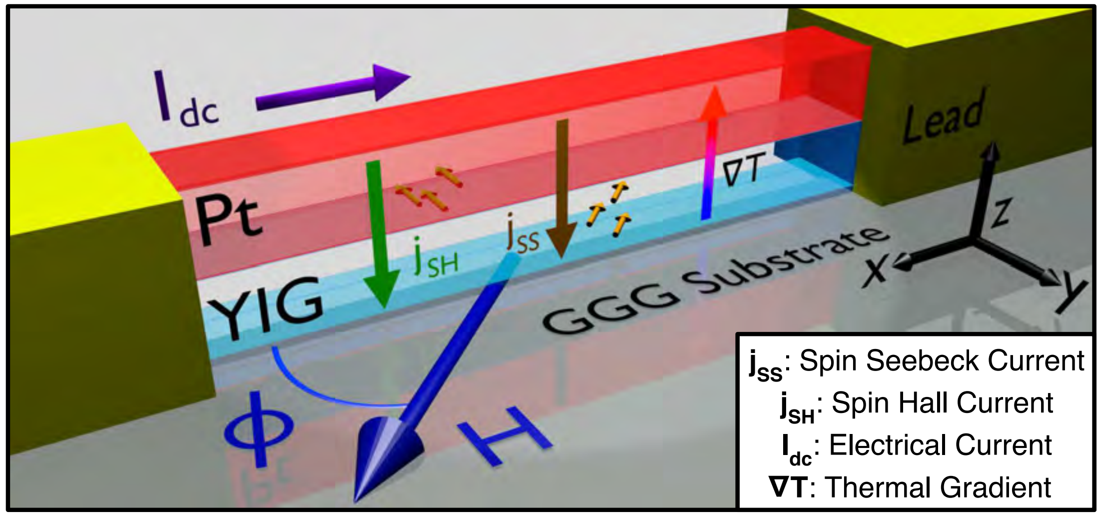
spin Seebeck pump:

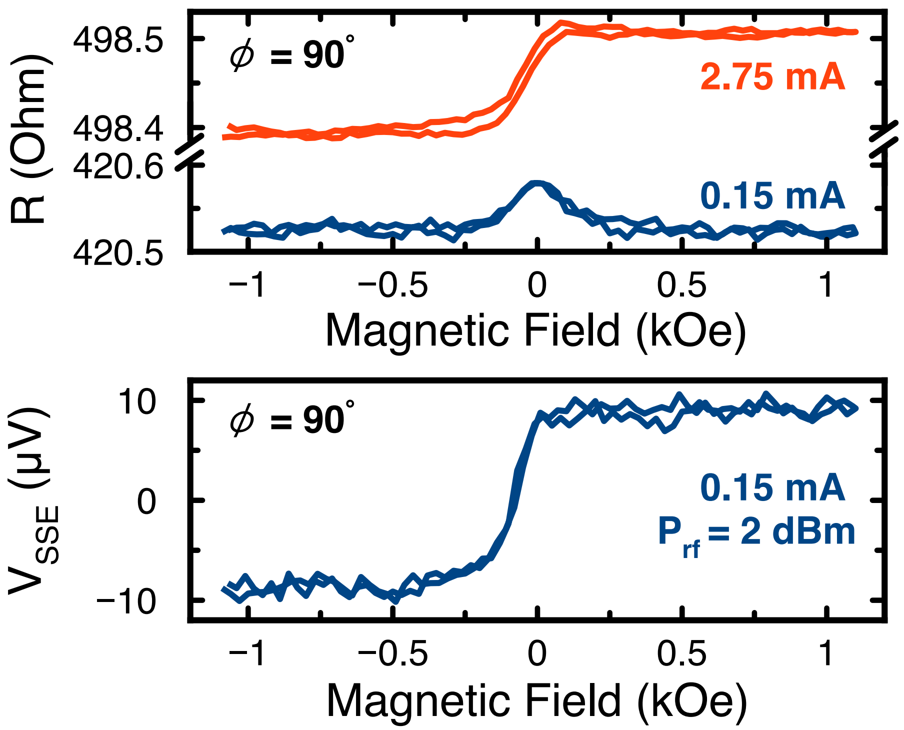


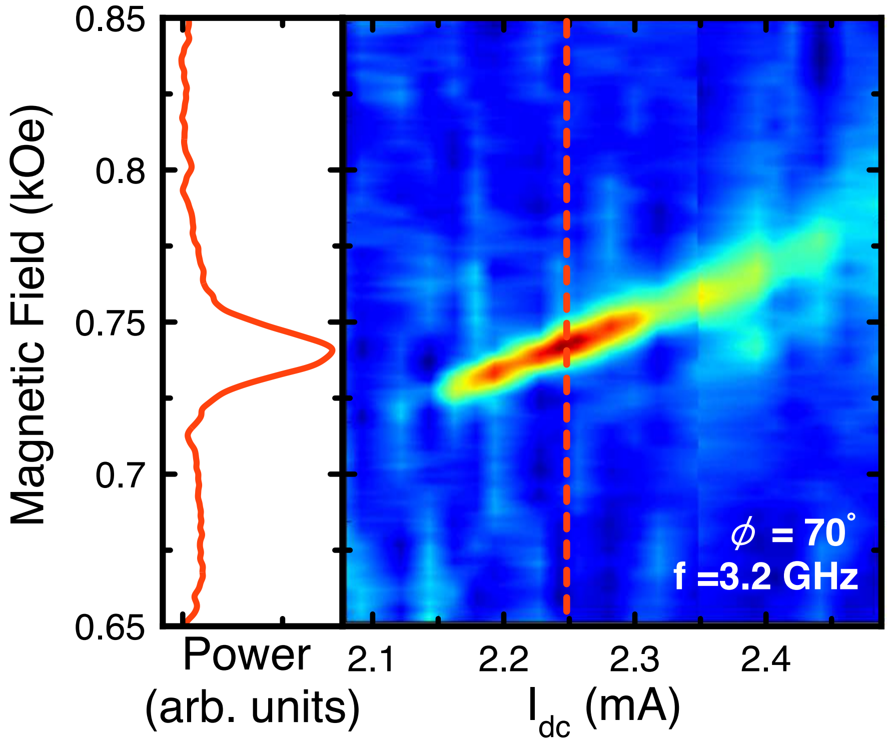


Safranski, Barsukov, Wu, YT, Krivorotov *et al., Nature Comm.* (2017)

Spin-caloritronic nano-oscillator



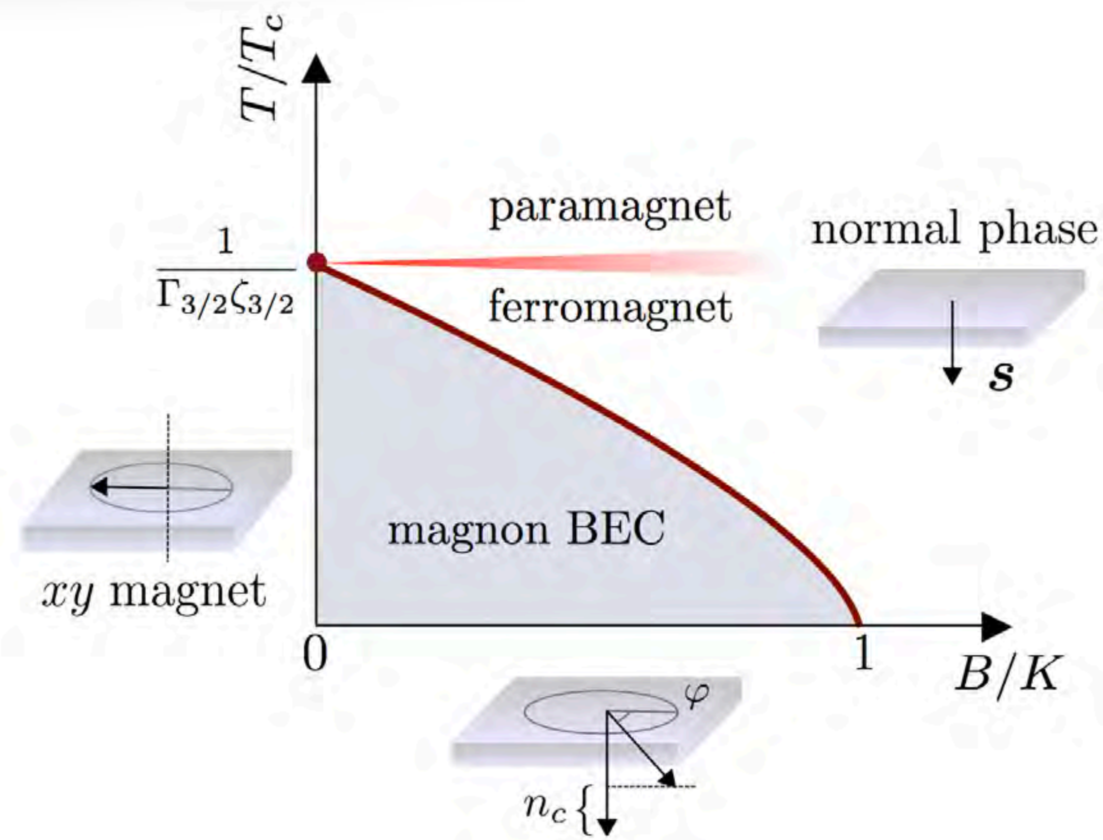


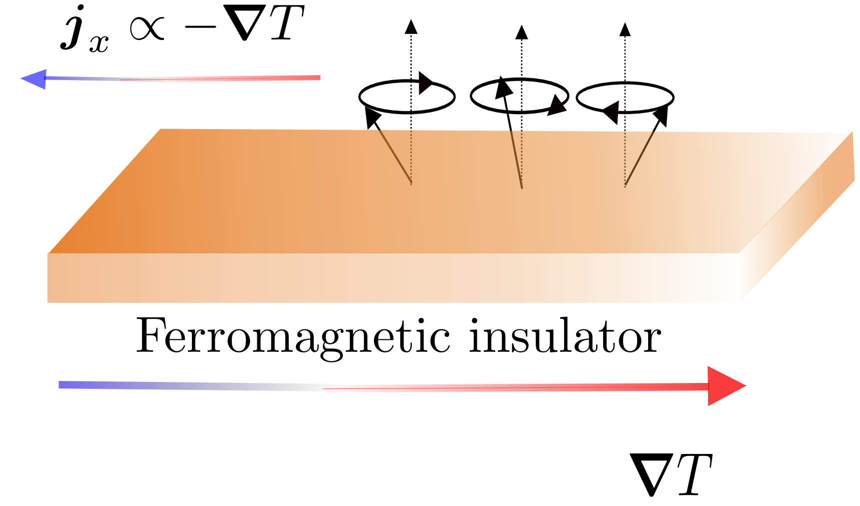


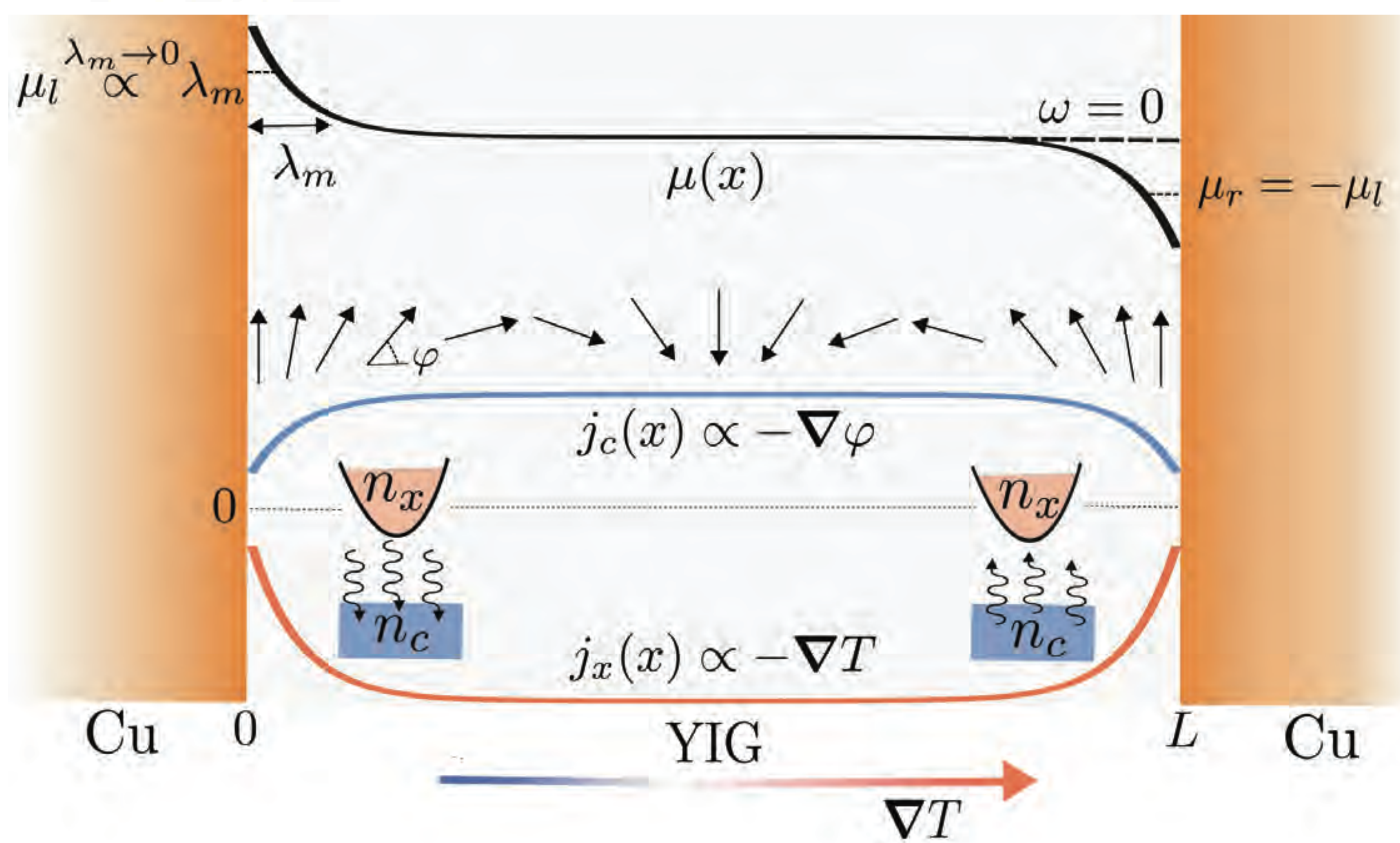
Safranski, Barsukov, YT, Wu, Krivorotov *et al., Nature Comm.* (2017)

See also: Lauer, Hillebrands, Chumak *et al., arXiv* (2016) for a pulsed measurement

Spin counterflow carried by superfluid

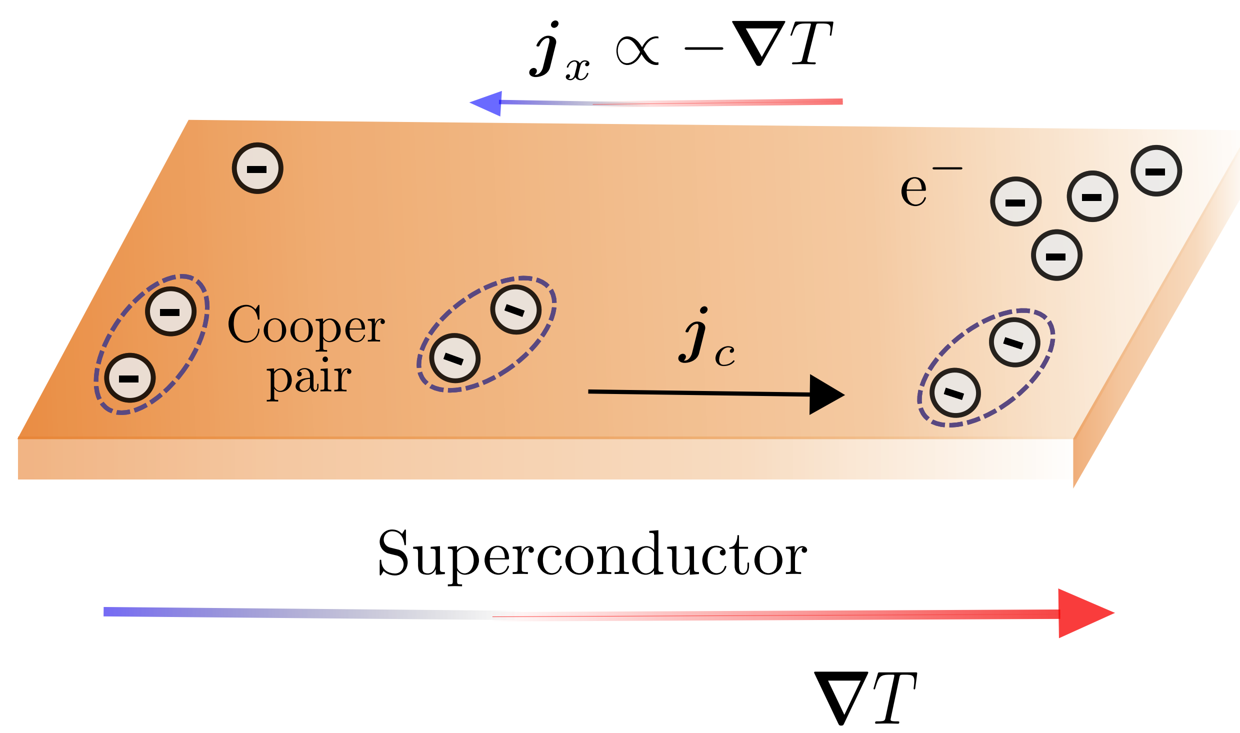






Flebus, Bender, YT, and Duine, *PRL* (2016)

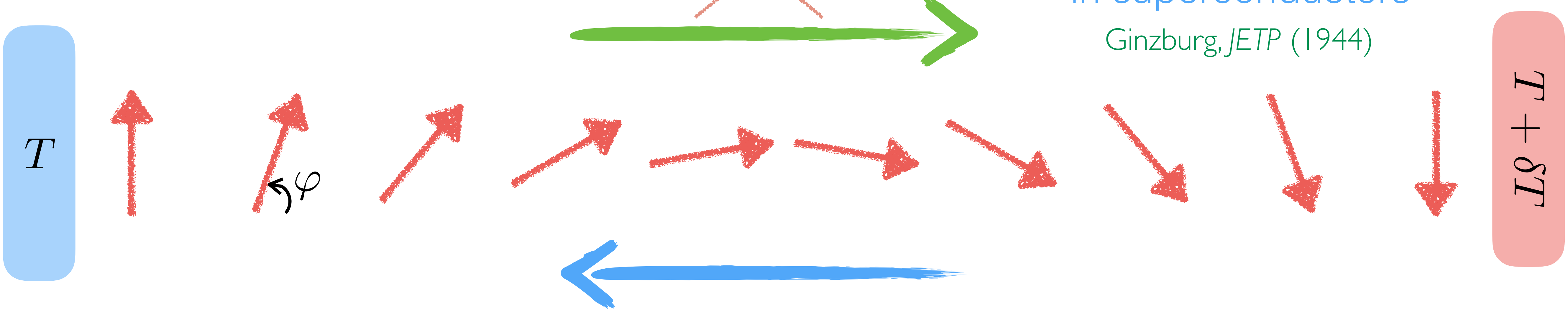
Thermal flows in conventional superfluids



$$\mathbf{j}_x = -\sigma(\boldsymbol{\nabla} V + \varsigma \boldsymbol{\nabla} T)$$

vanishing thermopower in superconductors

Ginzburg, *JETP* (1944)

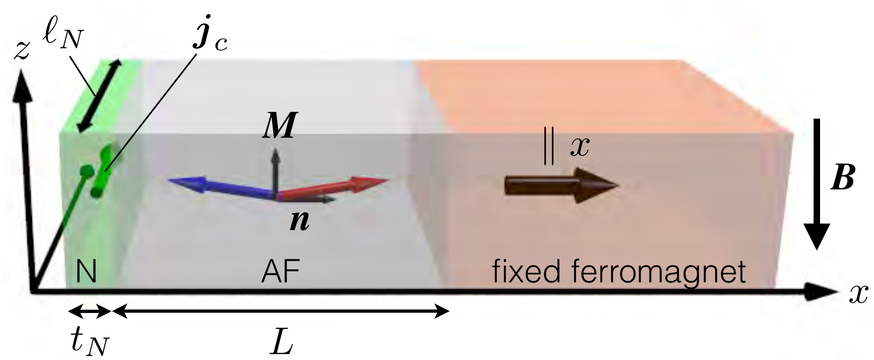


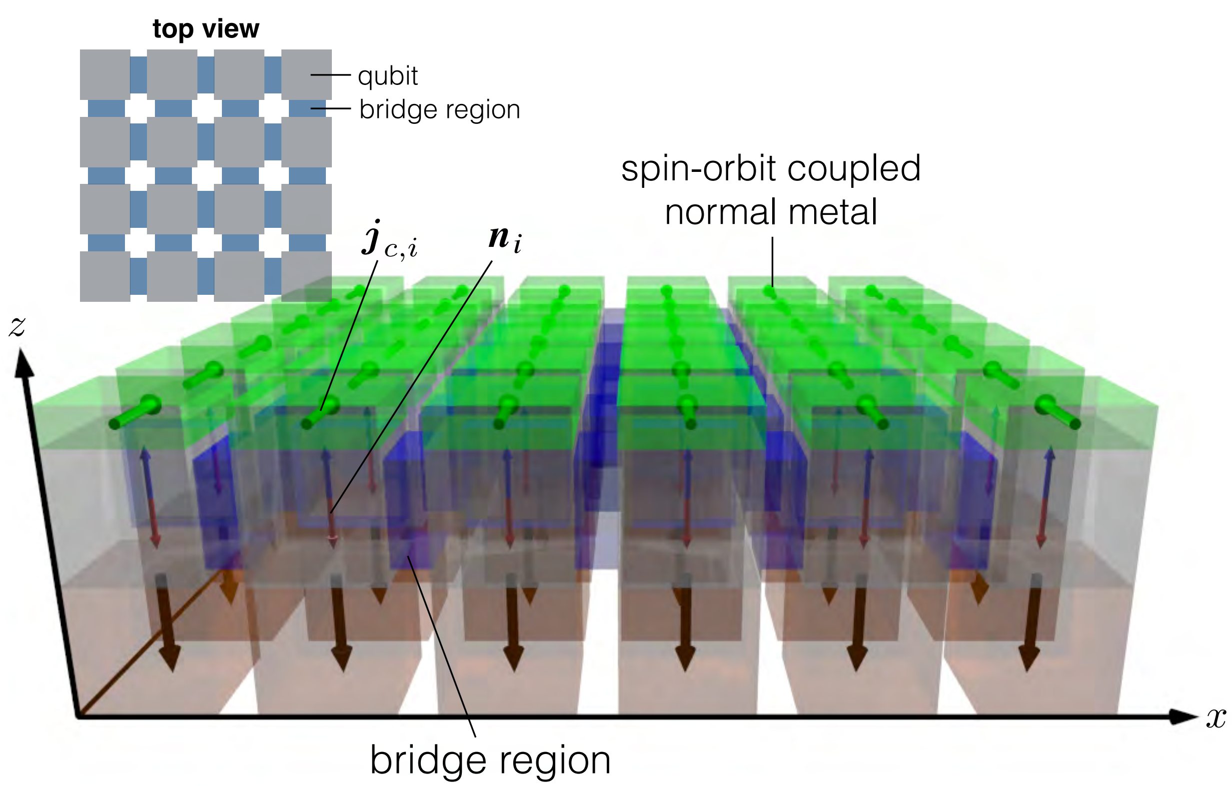
$$\mathbf{j}_s = -A \boldsymbol{\nabla} \varphi$$

nonentropic mass backflow: large heat conductivity in superfluids

Outlook towards quantum-information utility

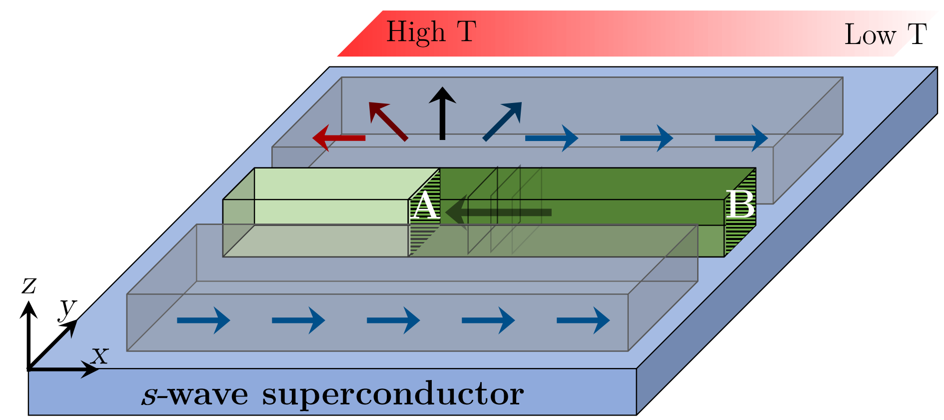
spin-superfluid phase qubit (controlled by spin Hall effect):

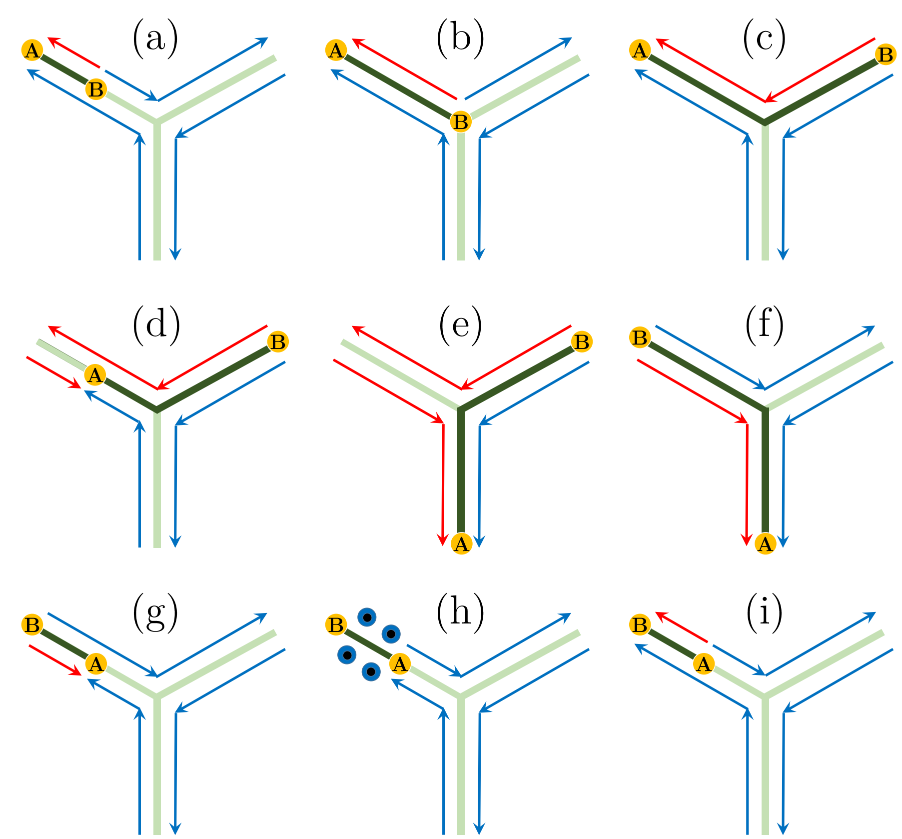




Takei, YT, and Mohseni, *PRB* (2017)

domain-wall manipulation of Majoranas (controlled by thermal torques):





Kim, Tewari, and YT, *PRB* (2015)

Summary/outlook

- Interplay/interconversion between the incoherent (thermal magnons) and coherent (order-parameter precession) magnetic dynamics can produce rich dynamic phase diagrams for the spin-Hall and spin-Seebeck driven heterostructures

- Of particular interest are the (steady-state) condensate phases, which are capable of harboring the spin superfluidity

- Spin condensates and superfluids, which are engendered and fed by the thermoelectric means offer an intriguing starting point for designing novel low-dissipation spintronic circuits that are based entirely on insulators

Thank you!

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