ELECTRONIC PUMPING OF QUASIEQUILIBRIUM BEC MAGNONS

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OUTLINE

BEC realizations of pumped collective excitations in CM

- BEC of exciton polaritons and photons in microcavities
- BEC of parametrically pumped magnons

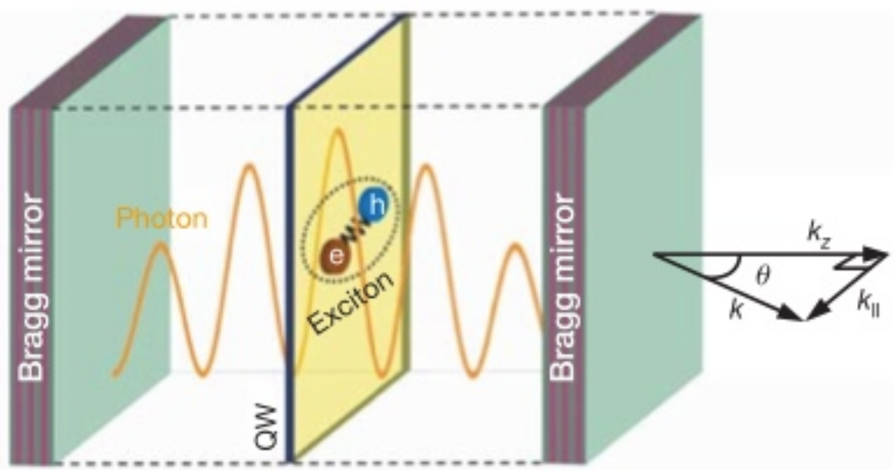
Spin pumping by magnons

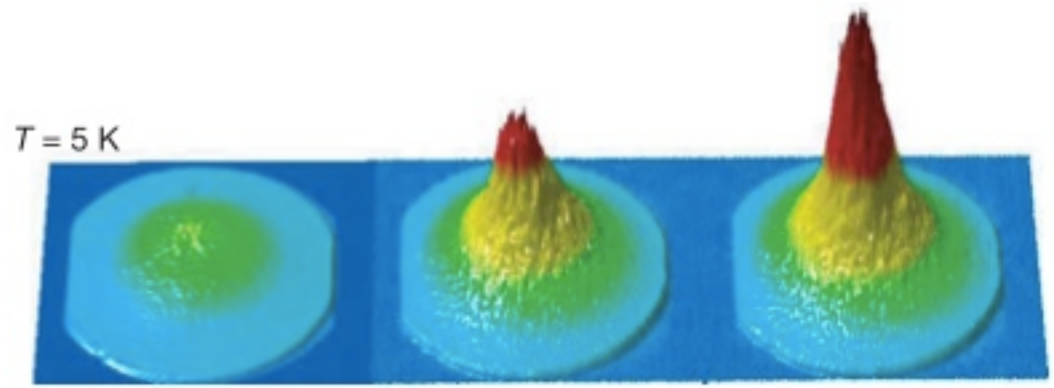
Spin-torque induced magnon BEC *vs* classical instabilities

Dynamic phase diagram/experimental proposal/feasibility (YIG)

BEC IN SOLID STATE

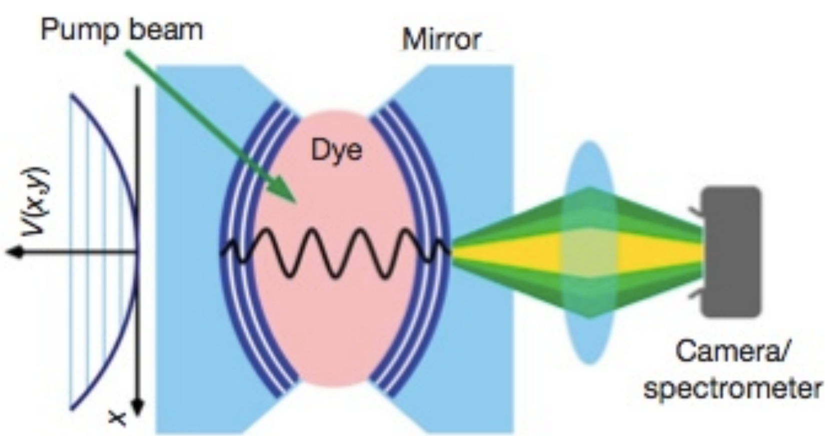
Exciton polaritons in semiconductor microcavities:

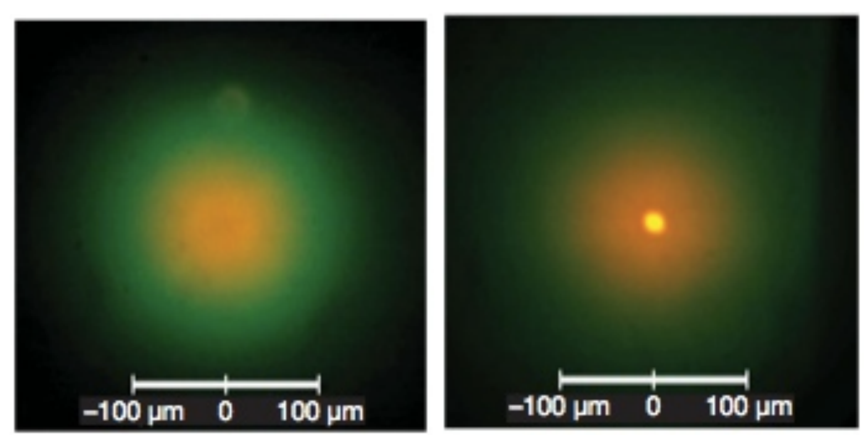




Deng *et al., Science* (2002); Kasprzak *et al., Nature* (2006); Balili *et al., Science* (2007)

Photons in an optical microcavity:

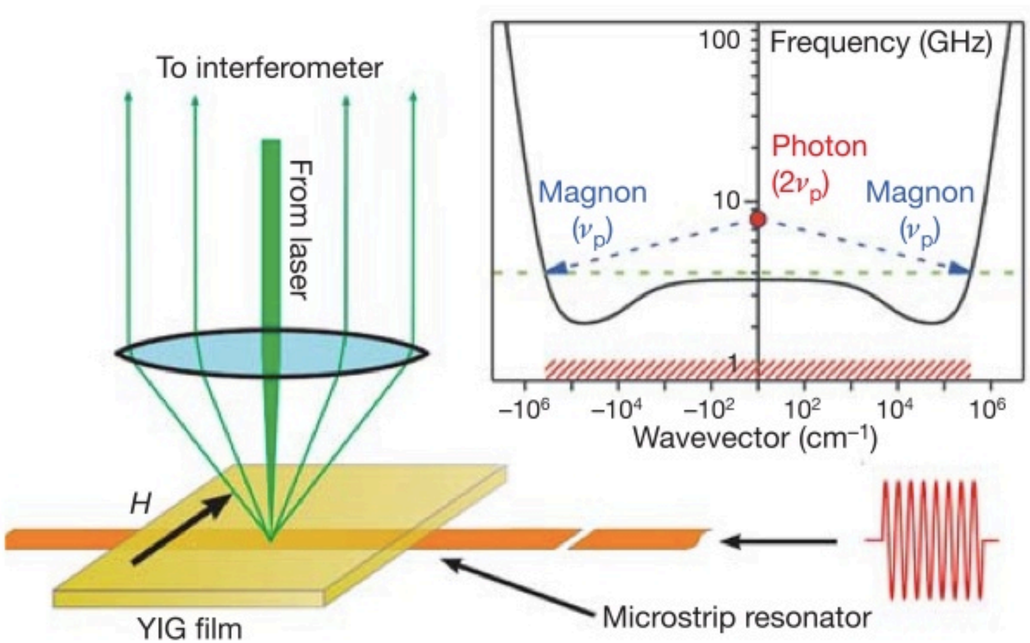




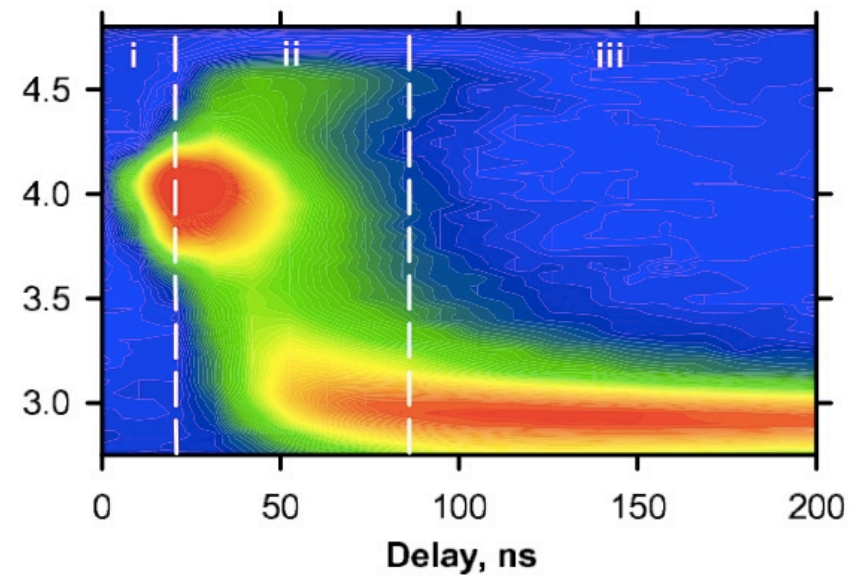
Klaers *et al., Nature* (2010)

BEC OF MAGNONS

Parametric microwave pumping of magnons in YIG:



Demokritov *et al., Nature* (2006)

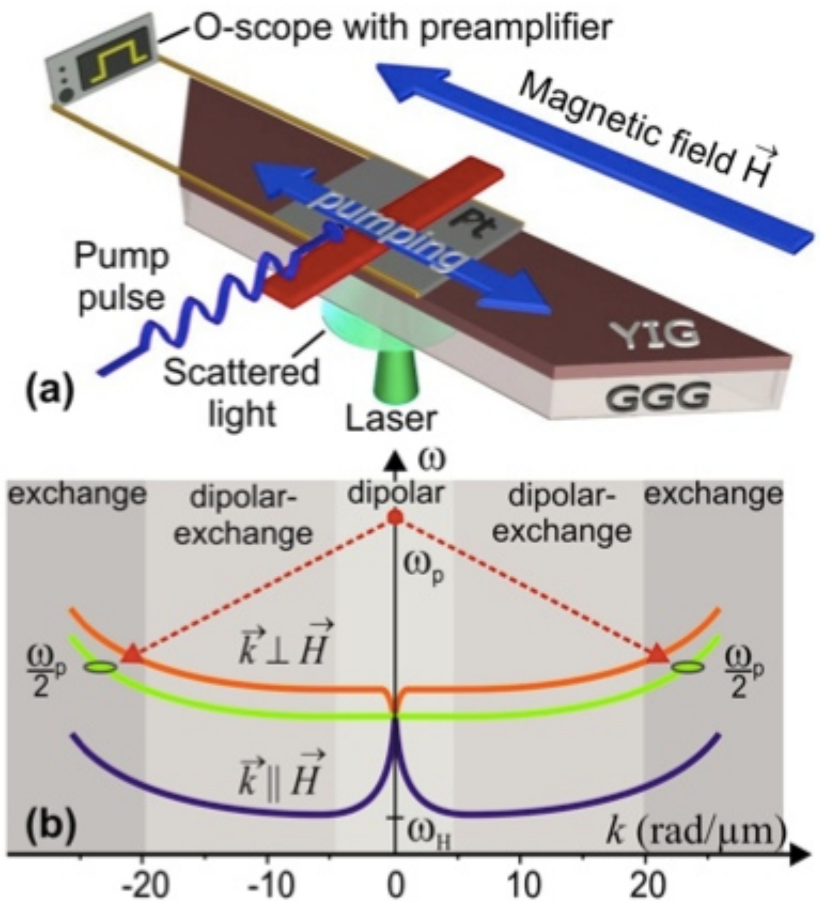


Demidov *et al., PRL* (2008)

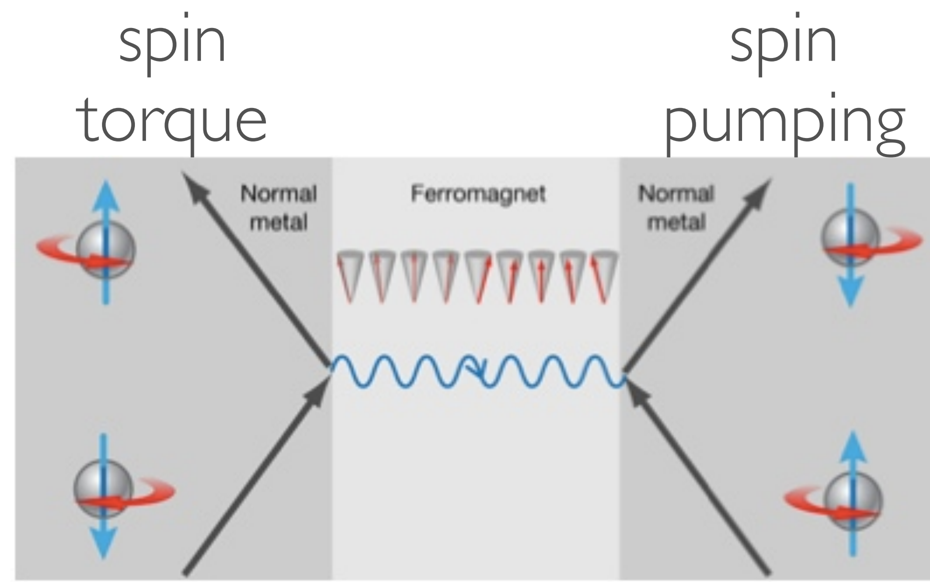
YIG is the material of the choice due to its low Gilbert damping

SPIN PUMPING BY MAGNONS

Parametrically pumped magnons induce ISHE voltage



Sandweg, Serga, Saitoh, Hillebrands *et al.*, *PRL* (2011)

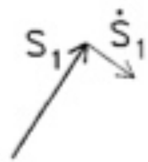


Bauer and YT, *Physics* (2011)

cf. Berger, *PRB* (1996)

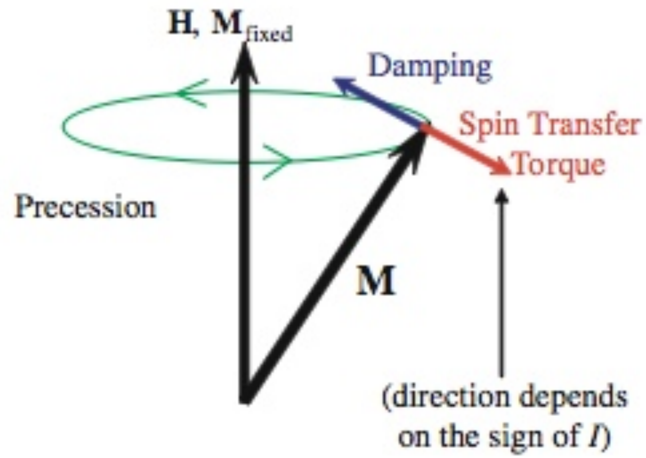
SPIN TORQUE *VS* SPIN PUMPING

The traditional picture of spin torque

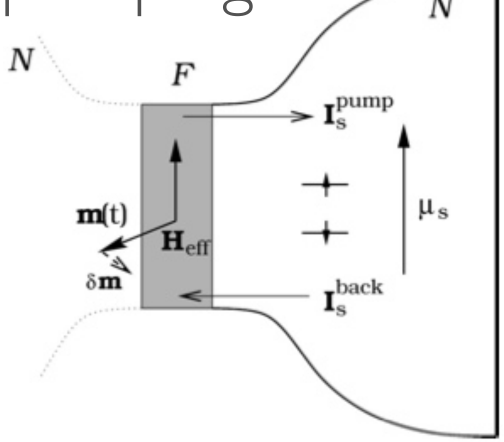


$$\dot{S}_1 = I(-\infty) - I(0)$$

Slonczewski, *JMMM* (1996)



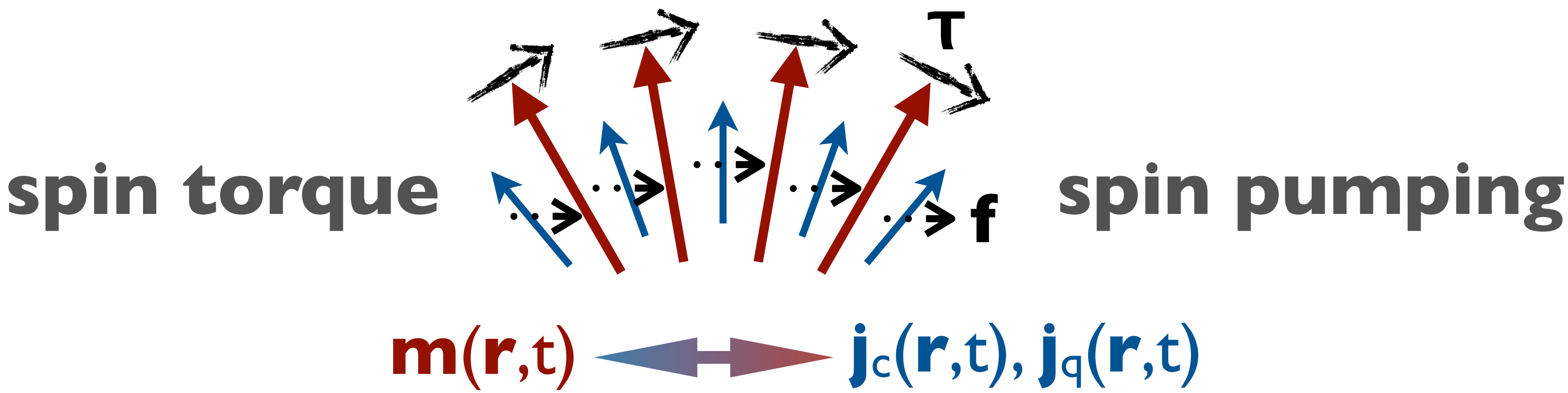
is accompanied with the thermodynamic reciprocal called spin pumping:



YT, Brataas, and Bauer, *PRL* (2002)

SPIN-TRANSFER RECIPROCITY

Interaction of magnetic spin textures and electric (charge/spin/heat) currents:

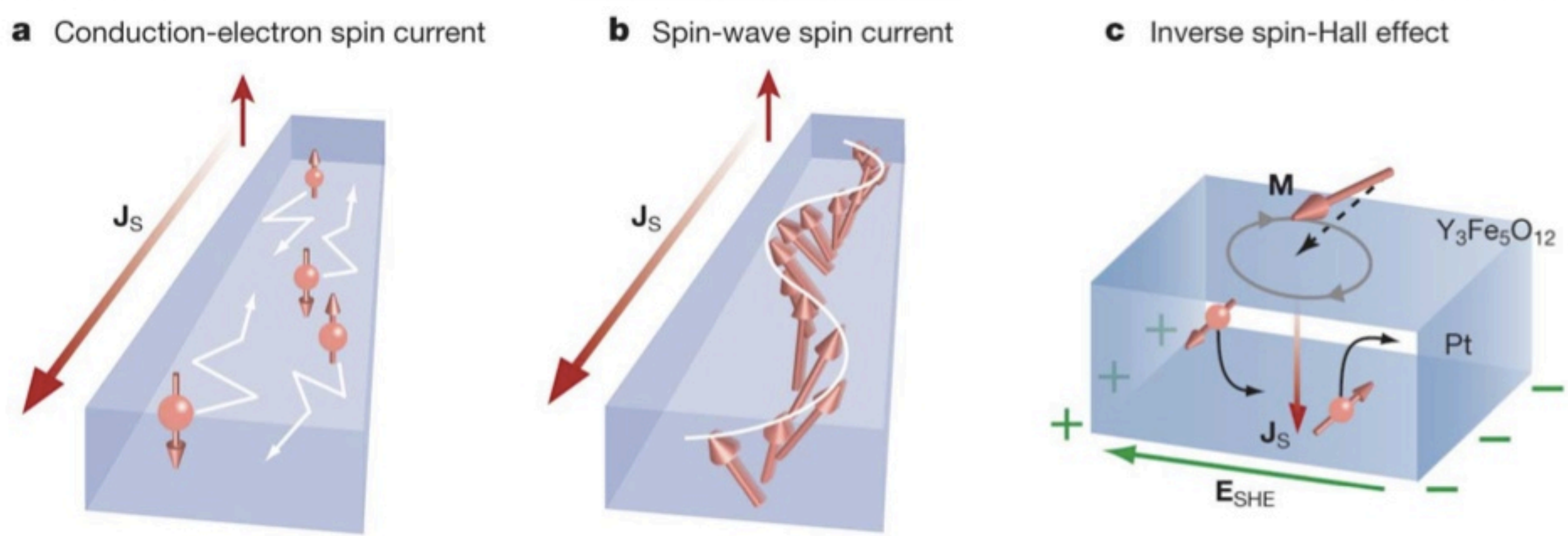


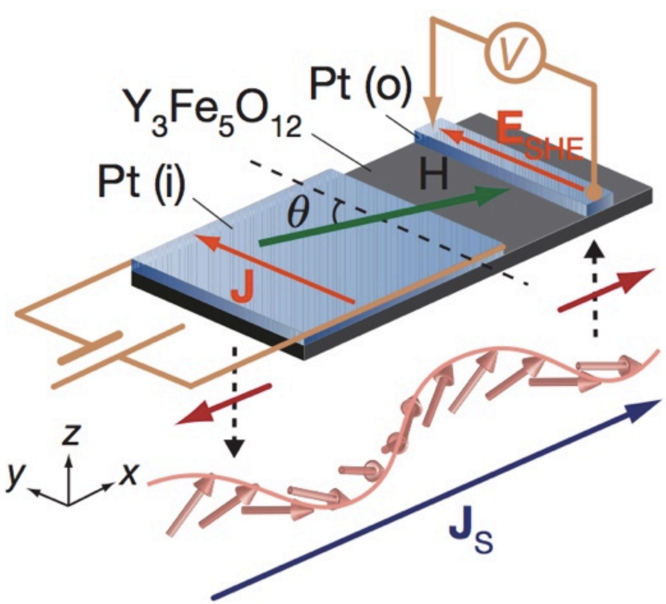
$$\partial_t \mathbf{m} - \alpha \mathbf{m} \times \partial_t \mathbf{m} = -\gamma \mathbf{m} \times \mathbf{H}_{\text{eff}} + \boldsymbol{\tau}$$

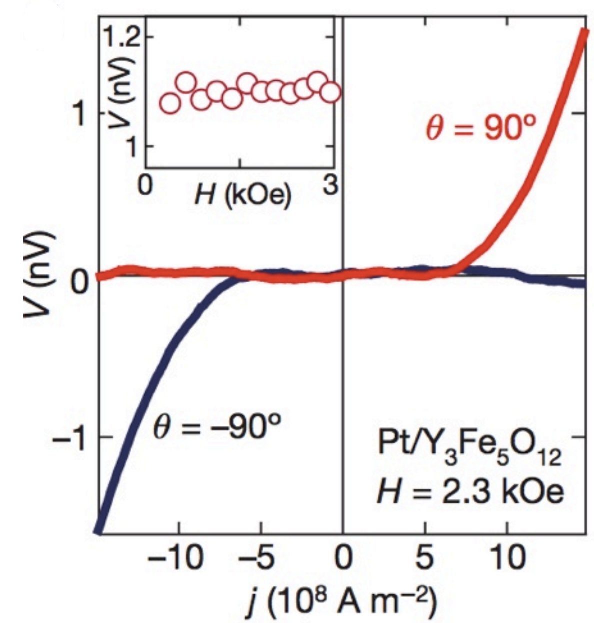
$$\hat{L}\partial_t \mathbf{j} + \hat{\rho}\mathbf{j} = \mathcal{E} + \mathbf{f}$$

YT and Mecklenburg (2008)
YT and Wong (2009)

SPIN-MAGNON EXCHANGE



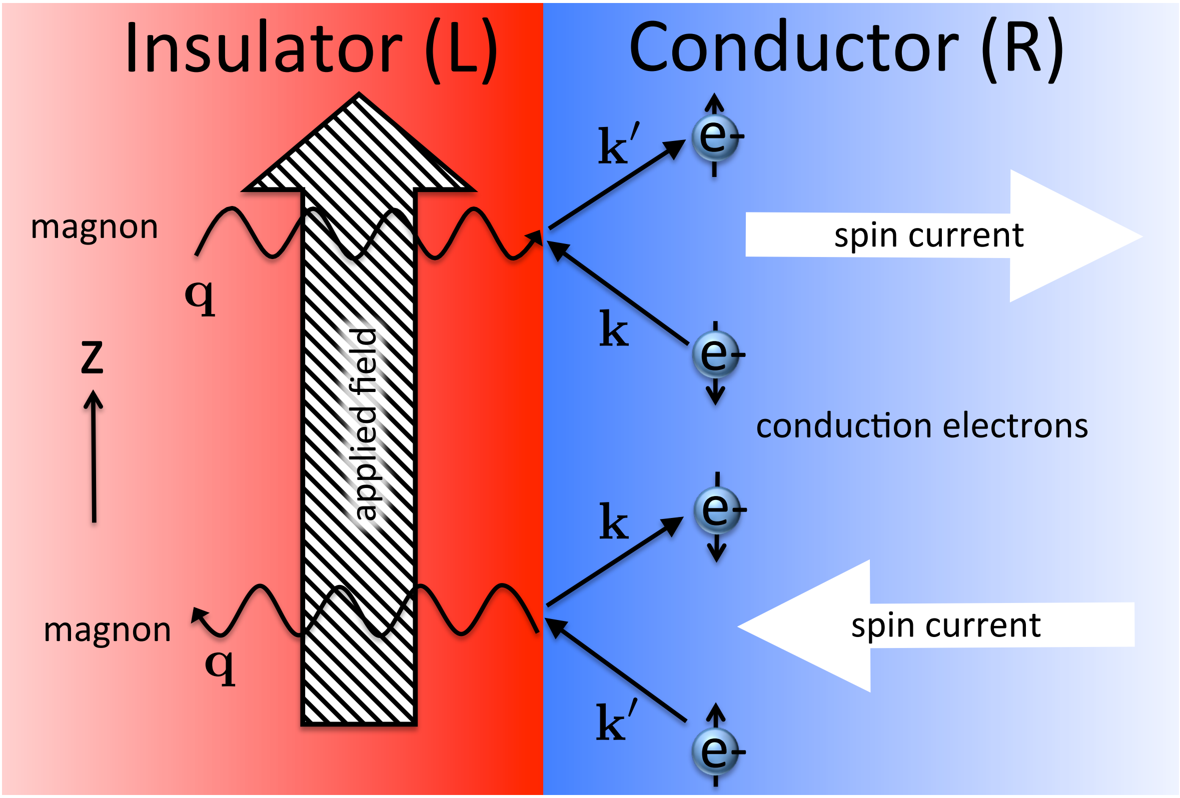




Kajiwara, Saitoh *et al.*, *Nature* (2010)

OUR GOAL

We want to develop a viable dc-transport route to inducing BEC of magnons in magnetic thin-film heterostructures

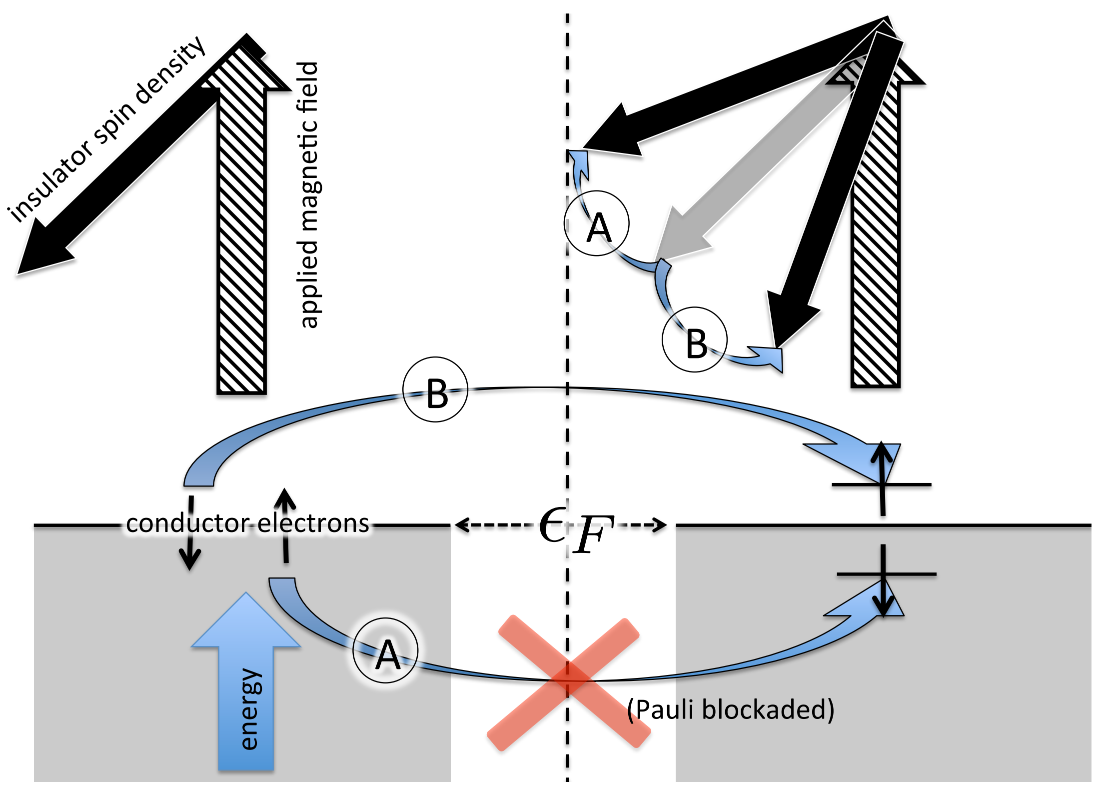


Microwave agitation of the ferromagnet is replaced by electronic spin pumping

Bender, Duine, and YT, *arXiv* (2011)

FI/NM INTERFACIAL EXCHANGE

$$\hat{V}_{\text{int}} = \sum_{\mathbf{qkk'}} V_{\mathbf{qkk'}} \hat{c}_{\mathbf{q}} \hat{a}^{\dagger}_{\mathbf{k'}\uparrow} \hat{a}_{\mathbf{k}\downarrow} + \text{H.c.}$$

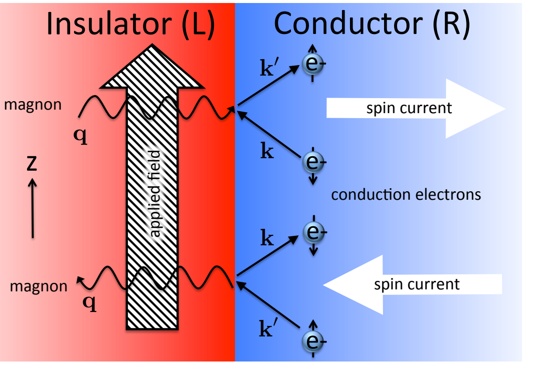


$$\Delta S_{\text{tot}} = \Delta S_R = \frac{1}{T_R} \left(\epsilon_{\text{gs}} - \Delta\mu \right) \Delta N_R$$

SPIN TRANSPORT EQUATIONS

The total (z axis) spin current

$$j = \frac{1}{A}\frac{d\langle S_L^z\rangle}{dt} = j_{\rm gs} + j_{\rm ex}$$



consists of the ground-state (condensed) magnon contribution

$$j_{\rm gs} = 2\pi\left|V_{\rm gs}\right|^2\left(\Delta\mu - \epsilon_{\rm gs}\right)g_R^2 n_{\rm gs}$$

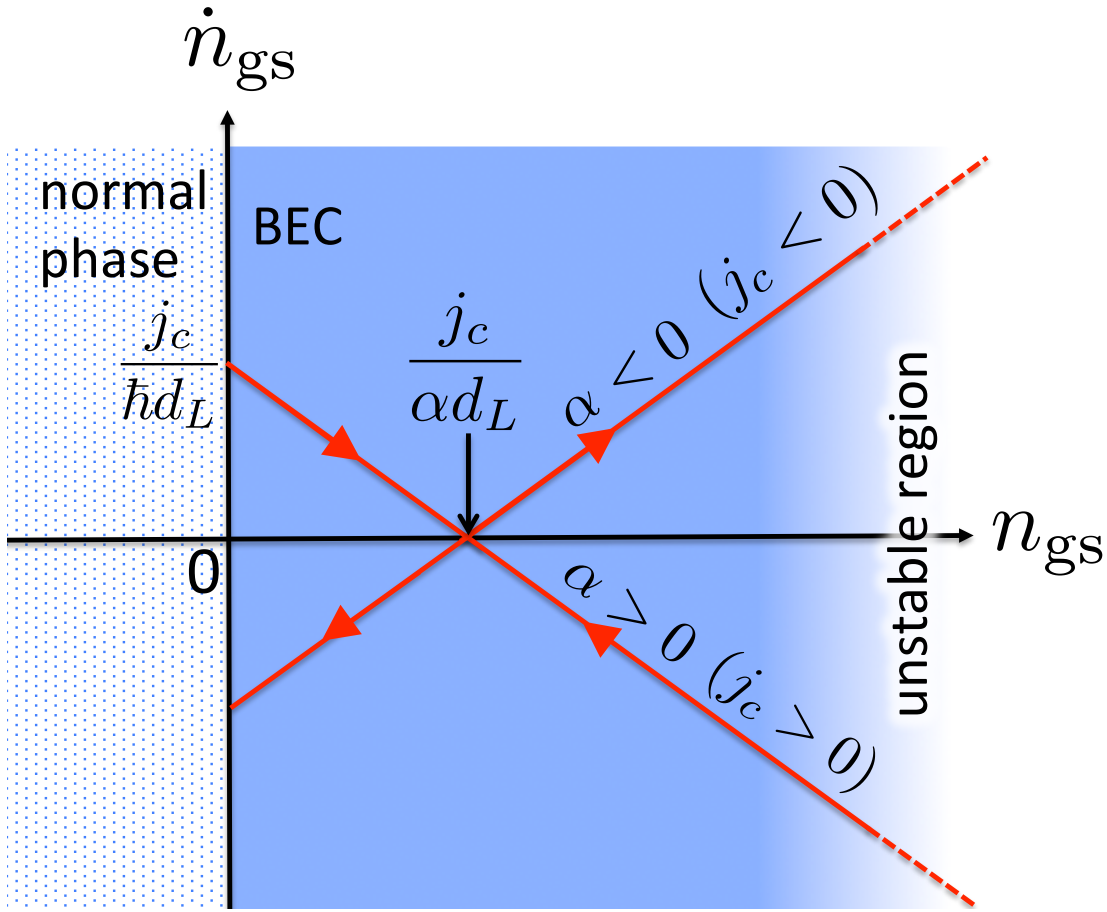
as well as the thermal magnon contribution

$$j_{\rm ex} = 2\pi\int_{\epsilon_{\rm gs}}^{\infty} d\epsilon\left|V_{\rm ex}(\epsilon)\right|^2\left(\Delta\mu - \epsilon\right)g_R^2 g_L(\epsilon) \times\left[n_{\rm B}\left(\beta_L(\epsilon-\mu_L)\right) - n_{\rm B}\left(\beta_R(\epsilon-\Delta\mu)\right)\right]$$

which is enhanced if $T_L < T_R$

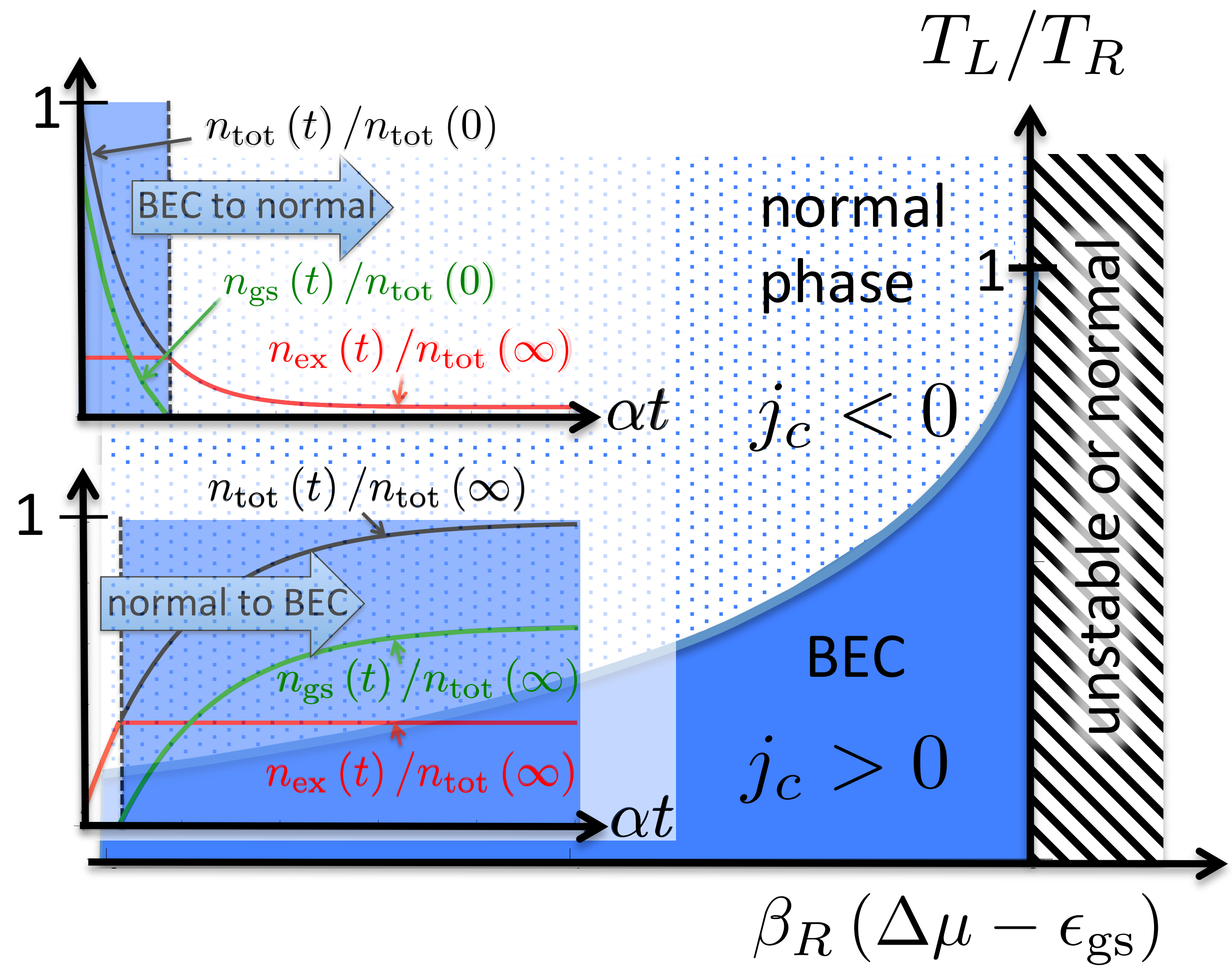
BEC RATE EQUATION

$$\dot{n}_{\rm gs} = j_{\rm tot}/\hbar d_L = j_c/\hbar d_L - \alpha n_{\rm gs}/\hbar \qquad \alpha = 2\pi \left|V_{\rm gs}\right|^2 (\epsilon_{\rm gs} - \Delta\mu)\, g_R^2/d_L$$



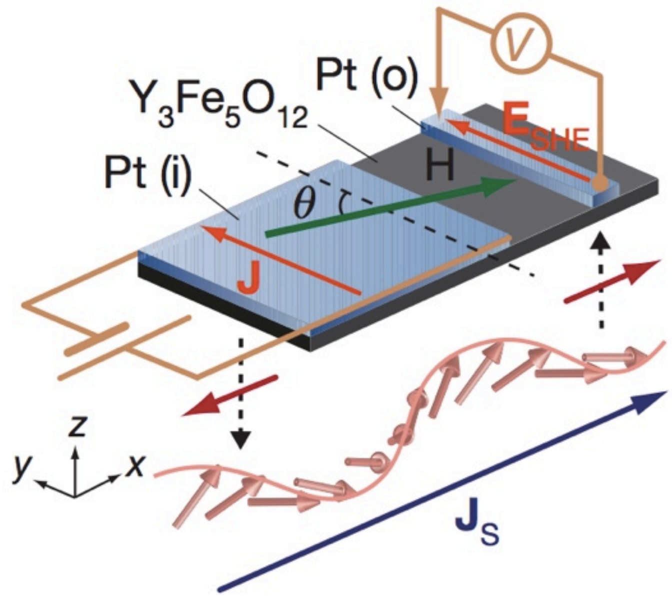
$$n_{\rm gs}(t) = \frac{j_c}{\alpha d_L} + \left[n_{\rm gs}(0) - \frac{j_c}{\alpha d_L}\right] e^{-\alpha t/\hbar}$$

DYNAMIC PHASE DIAGRAM



EXPERIMENTAL PROPOSAL

Starting with the classical spin-torque instability in YIG/PT bilayer



Kajiwara, Saitoh *et al.*, *Nature* (2010)

- reduce the Pt SHE current slightly below its critical value
- thermally anchor YIG layer relative to Pt by a cool substrate

The larger the YIG/PT temperature difference, the wider the subcritical current window for the BEC phase

DETECTION AND OUTLOOK

The proof-of-principle for transport-induced BEC of magnons can be confirmed by Brillouin light scattering or detection of coherent microwave emission (with BEC coherence reflected in the characteristic scaling of signal with lateral size of the YIG/Pt bilayer)

The dc steady-state realization of BEC would open new avenues for realization of superfluidity, macroscopic coherent phenomena, and nonlocal transport scenarios that are not feasible in a traditional microwave-pumped realization of magnon condensates

First condensed-matter realization of BEC of bosonic excitations in an electrically-driven system?

SUMMARY

The quantized form of spin-transfer torque and pumping captures both the classical Gilbert damping and torque-driven instabilities

This description also provides a natural language for discussing dilute electronically-pumped magnon gases, which can condense in a steady-state dc transport regime, requiring

- (SHE) current-induced classical instability in a magnetic insulator film with low intrinsic Gilbert damping (compared to spin pumping): $d \lesssim 1\ \mu\mathrm{m}$
- cooling the magnetic layer relative to the normal-metal layer (Seebeck)
- optical/microwave/nonlocal transport probes to confirm coherence of the condensate