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Coupling of heat and spin currents at the nanoscale in cuprates and metallic multilayers

David G. Cahill, Greg Hohensee, and Gyung-Min Choi
Department of Materials Science and Engineering
University of Illinois at Urbana-Champaign

Thanks to Rich Wilson, 2-channel modeling; and Byoung-Chul Min and Kyung-Jin Lee (Spin Convergence Research Center, Korea Institute of Science and Technology) for initial samples, and magnetization dynamics modeling

supported by Army Research Office

Hohensee *et al.*, PRB (2014)

Choi *et al.*, *Nature Communications* (2014)

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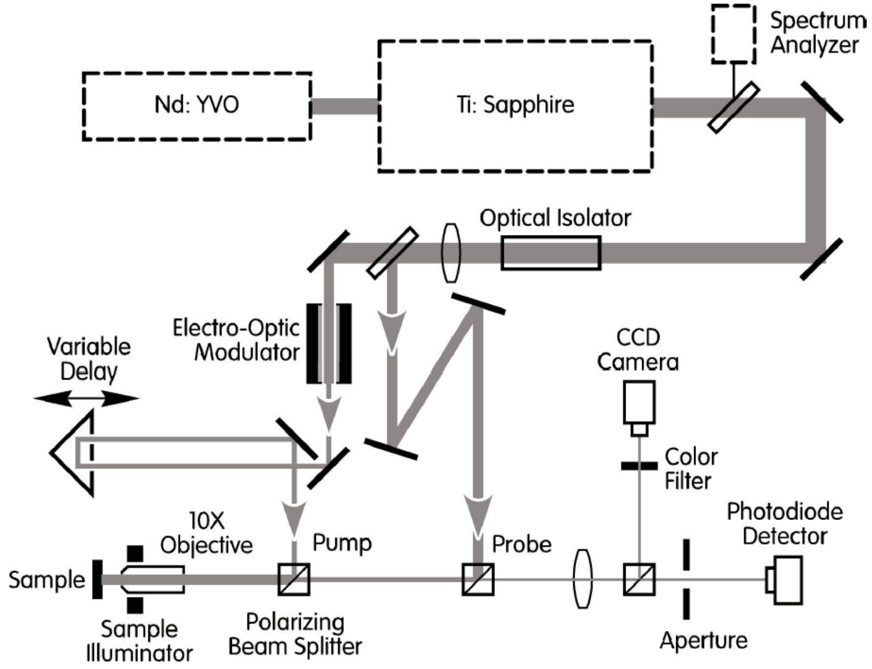
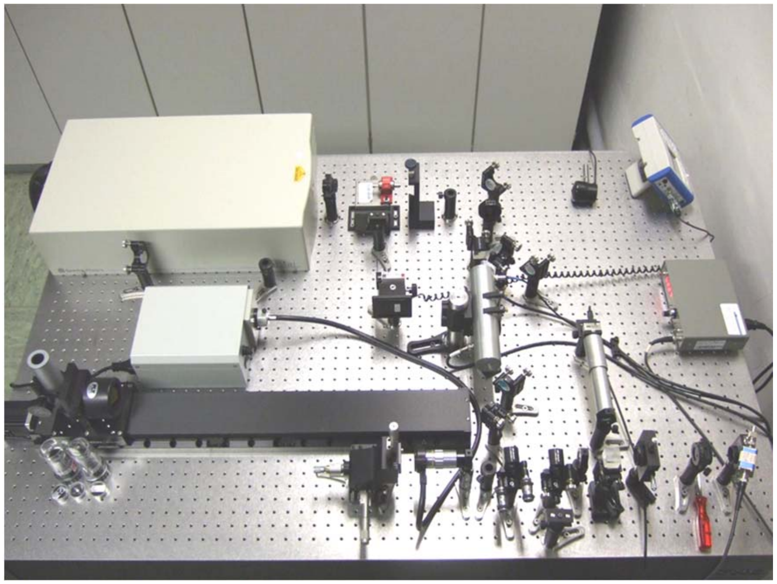
Outline

- Part I: Extremes. Heat conduction by spin waves in one-dimensional quantum spin systems
  - Determine strength of magnon-phonon coupling using frequency dependence of the thermal conductivity as measured by time-domain thermoreflectance.
- Part II: New thermal function. Spin-heat current coupling in metallic multilayers
  - produce a spin current by ultrafast heat flow through a CoPt perpendicular magnetic layer.
  - Kerr effect probe of transient spin polarization of a Cu capping layer.
  - Kerr effect probe of spin-torque effect on an in-plane magnetic layer.

Time domain thermoreflectance since 2003

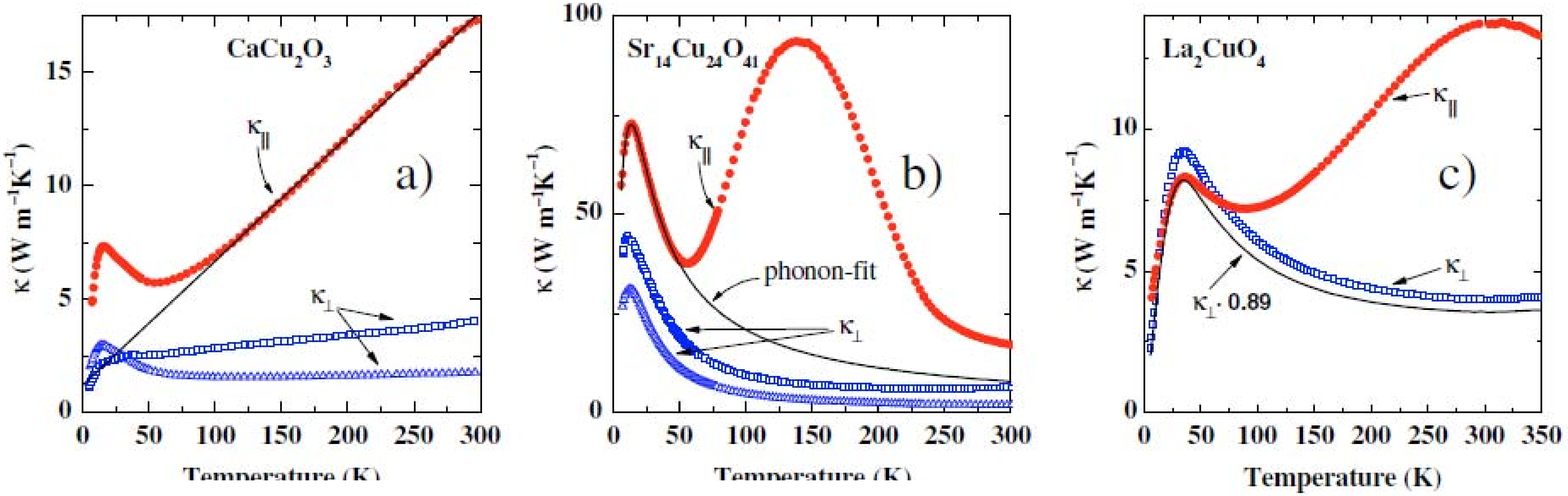
- Improved optical design
- Normalization by out-of-phase signal eliminates artifacts, increases dynamic range and improves sensitivity
- Exact analytical model for Gaussian beams and arbitrary layered geometries
- One-laser/two-color approach tolerates diffuse scattering

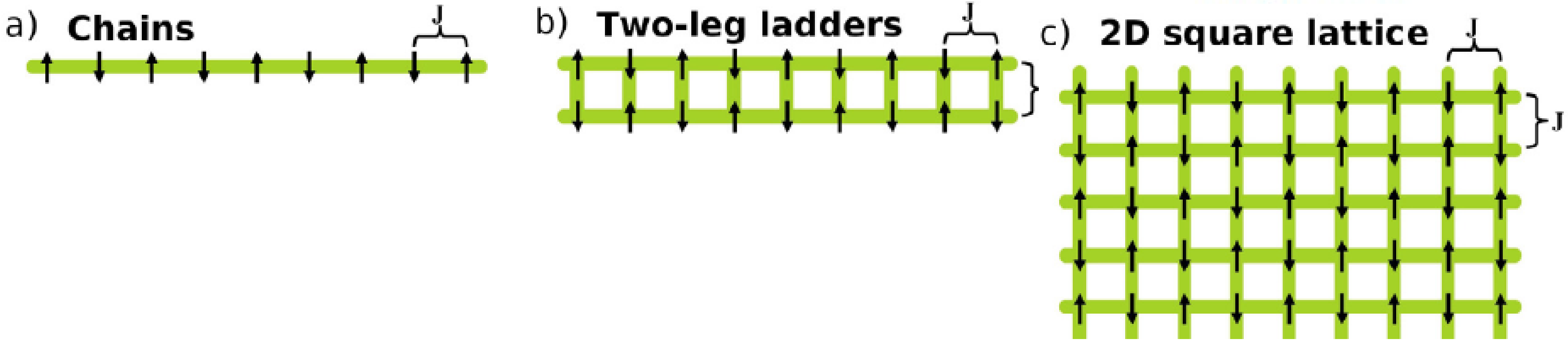




Clone built at Fraunhofer Institute for Physical Measurement, Jan. 7-8 2008

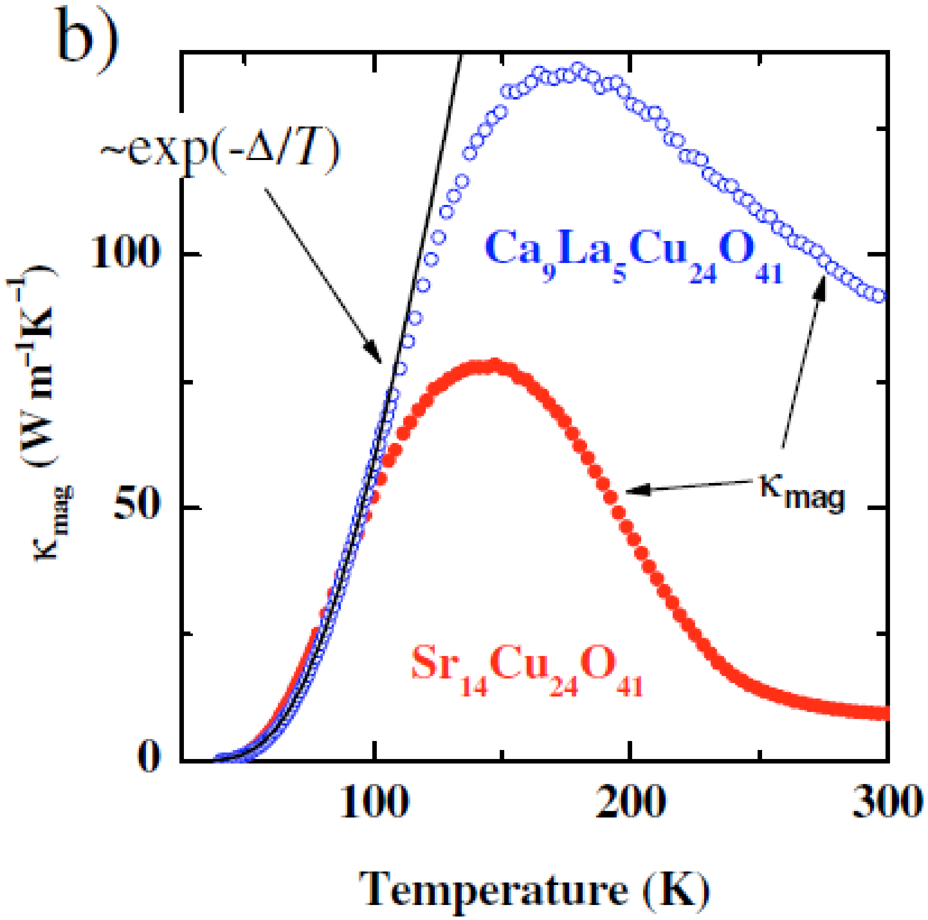
Diversity of anti-ferromagnetic order in copper-oxides





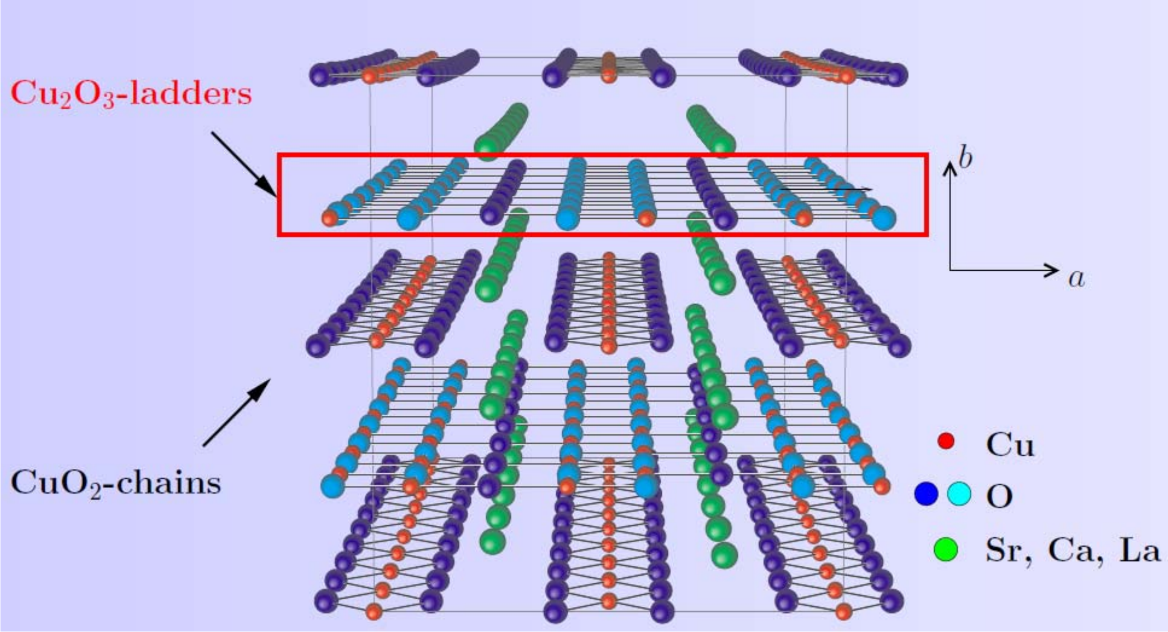
Hess (2007)

Reports of extraordinarily high spin-wave thermal conductivity near room temperature in "undoped" ladder



Hess (2007)

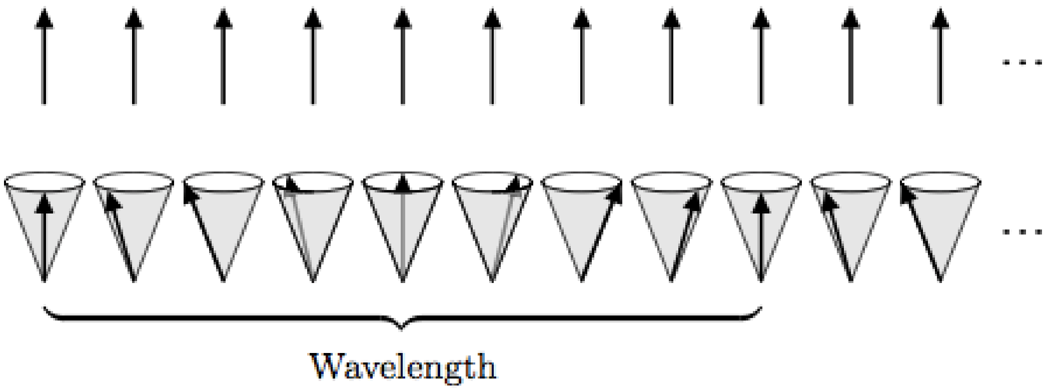
Magnon-phonon coupIng and magnon thermal conductivity in the spin ladder $Ca_9La_5Cu_{24}O_{41}$



McCarron *et al.*, Mat. Res. Bull. (1988)

colorized graphic by Heidrich-Meisner (2005)

Spin waves are intrinsically quantum mechanical so hard to think about in classical analogies

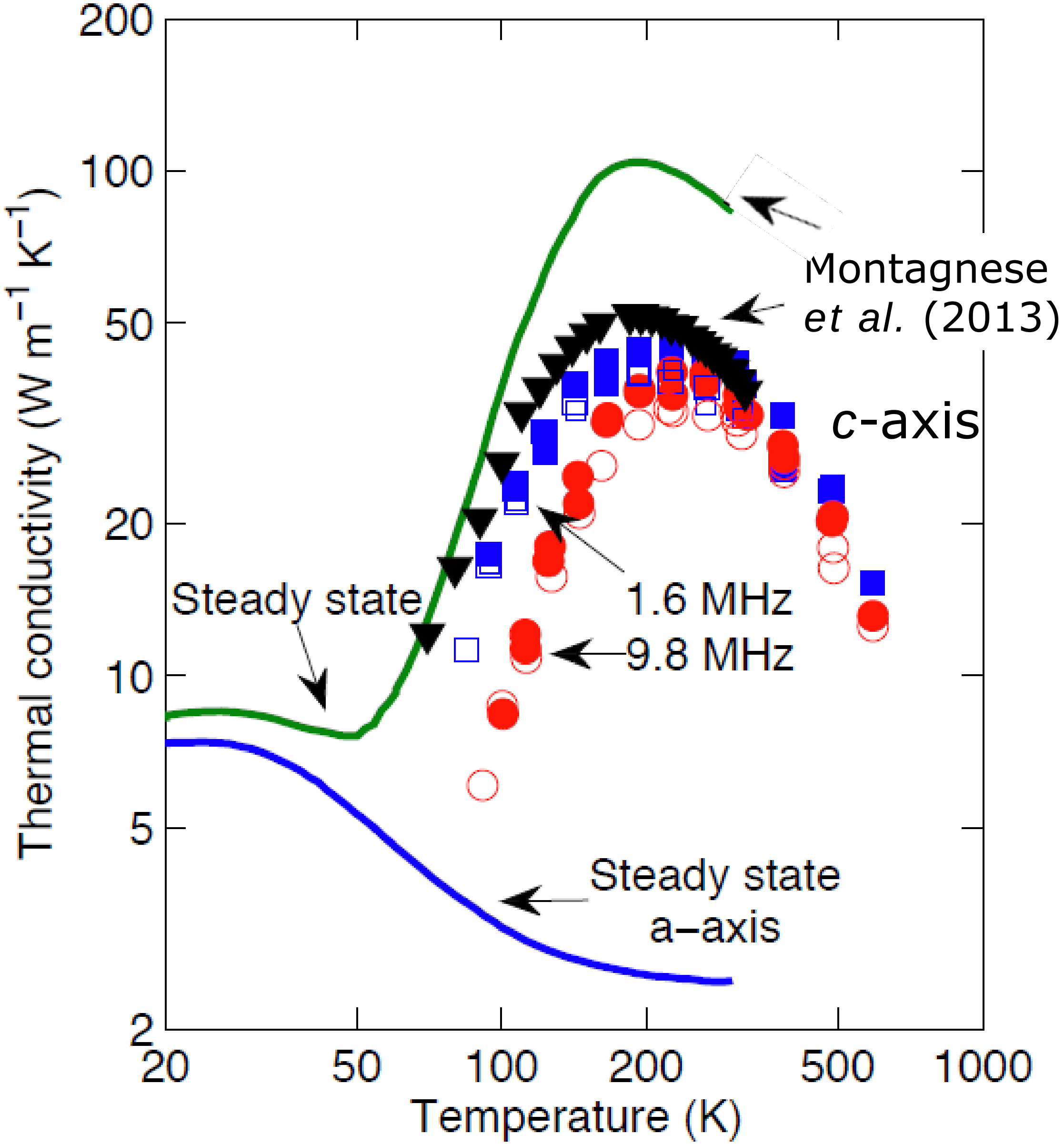


Ferromagnetic
ground state

Thermally-excited
spin-wave state

http://www.physics.usyd.edu.au/~sflammia/Courses/StatMech/advanced/4/a4.html

Frequency dependent spin-wave thermal conductivity in $Ca_9La_5Cu_{24}O_{41}$

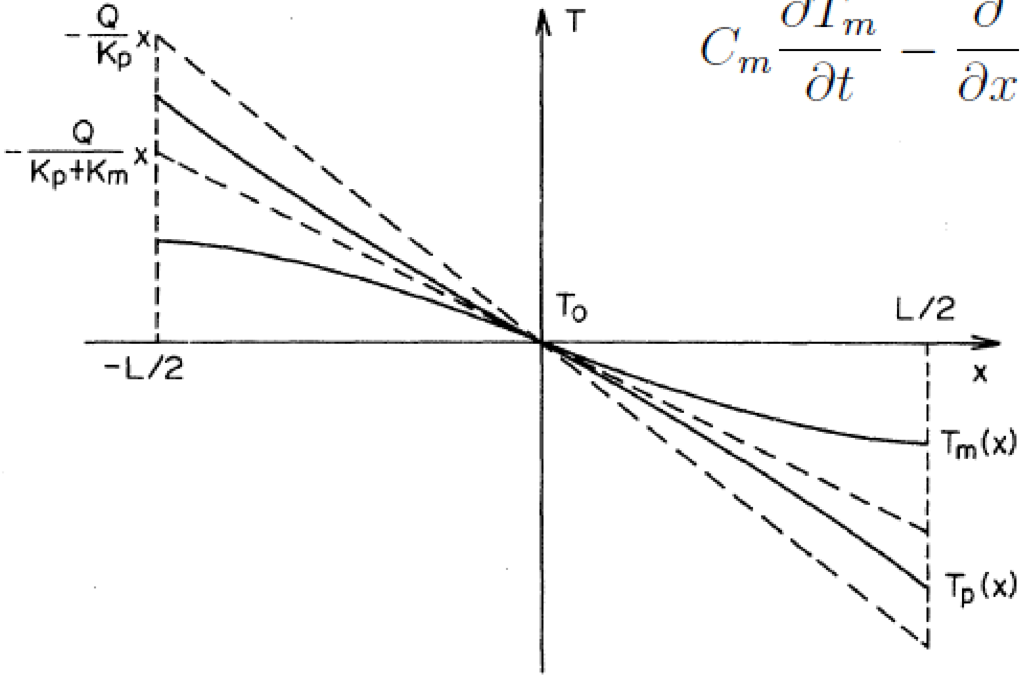


Use a two-channel model: magnons and phonons

- Sanders and Walton (1977) analyzed the steady-state situation for the context of conventional thermal conductivity measurements. Only phonons can carry heat through the ends of the sample.

$$C_p \frac{\partial T_p}{\partial t} - \frac{\partial}{\partial x}\left(\Lambda_p \frac{\partial T_p}{\partial x}\right) + g(T_p - T_m) = 0$$

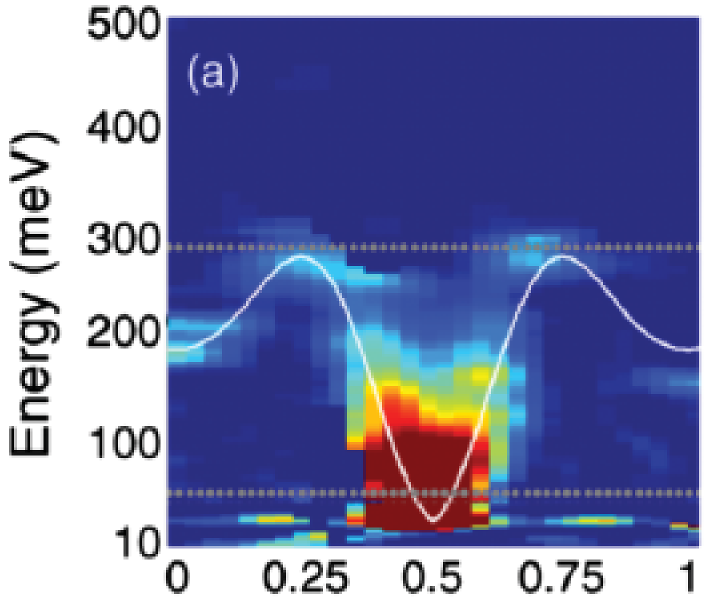
$$C_m \frac{\partial T_m}{\partial t} - \frac{\partial}{\partial x}\left(\Lambda_m \frac{\partial T_m}{\partial x}\right) + g(T_m - T_p) = 0.$$



Solution for TDTR experiments: Wilson *et al*., PRB (2013).

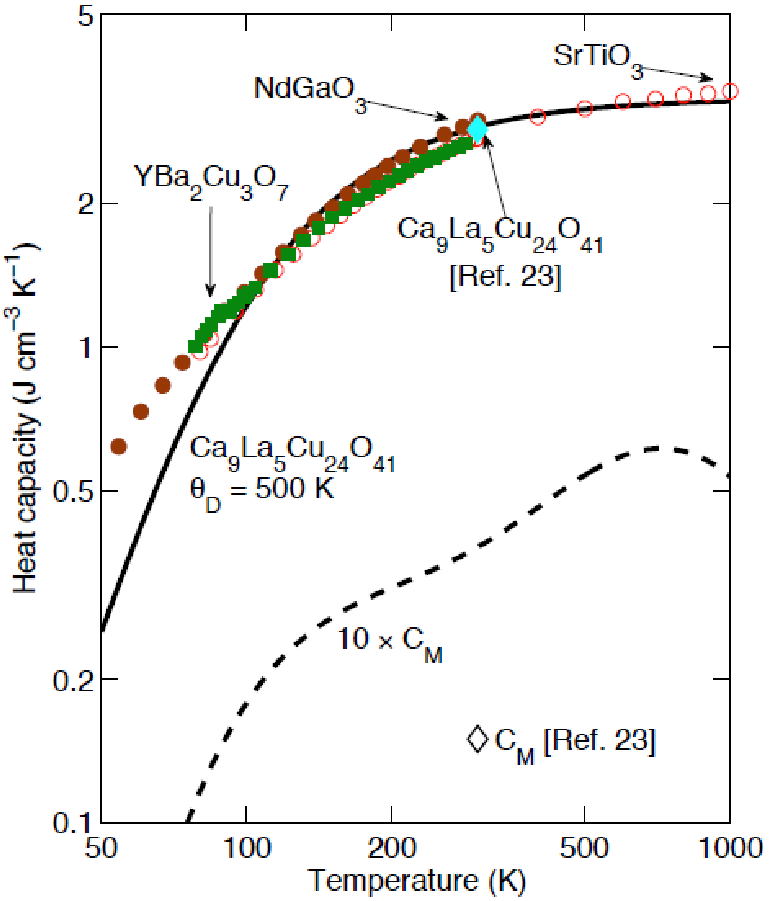
Need to fix as many parameters as possible

- Use magnon dispersion to estimate magnon heat capacity.
- Lattice and magnon thermal conductivity from Montagnese *et al*. (2013)



Notbohm, PRL 2007

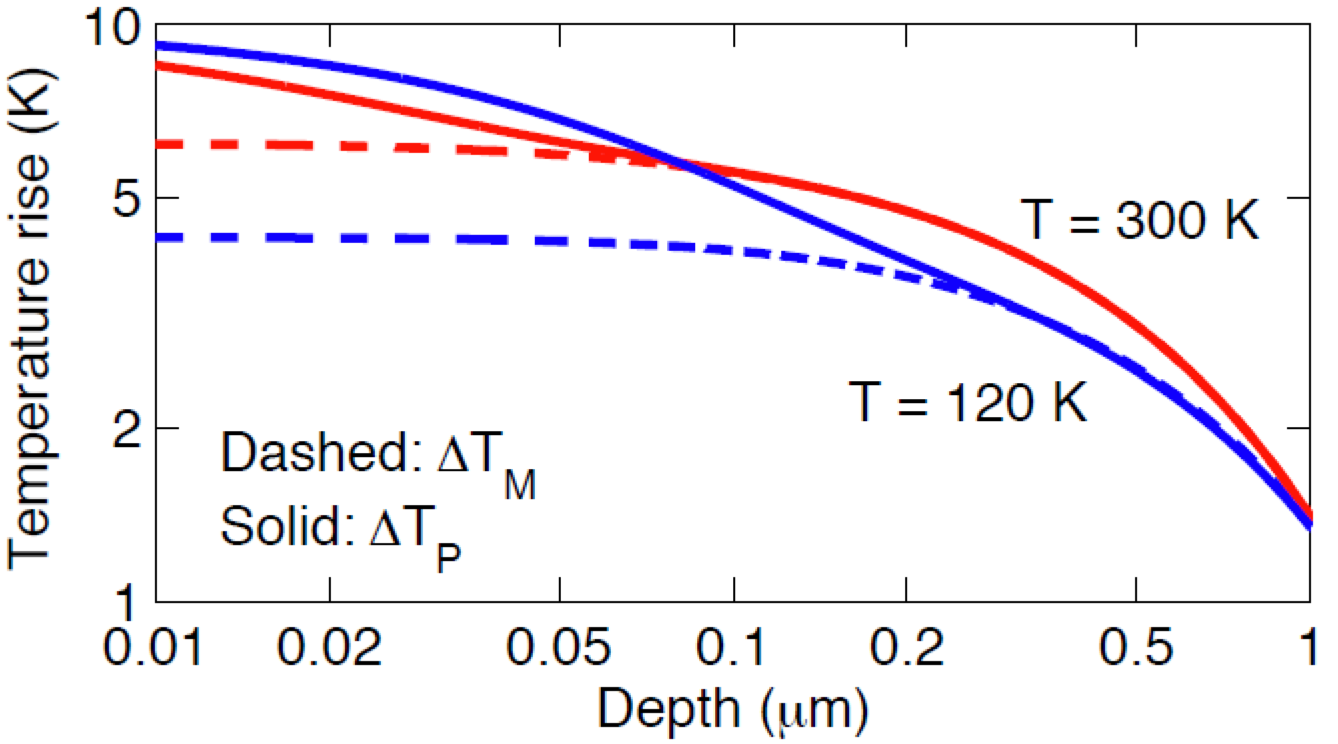
(inelastic neutron scattering)



Hohensee *et al*., PRB (2014)

Use a two-channel model: magnons and phonons

- Model calculations for 10 MHz TDTR experiment. The coupling parameter g is adjusted to get the best fit to the frequency dependent data

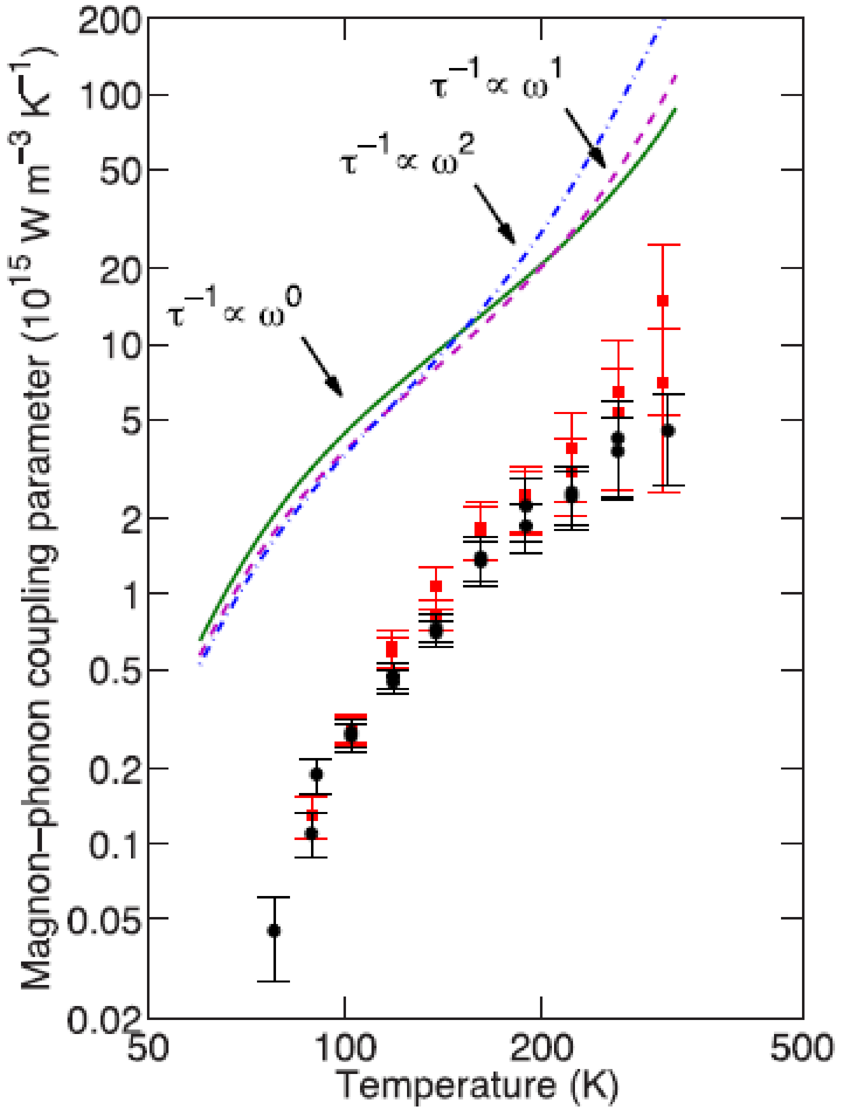


Hohensee *et al*., PRB (2014)

Magnon-phonon coupling parameter is strongly *T*-dependent

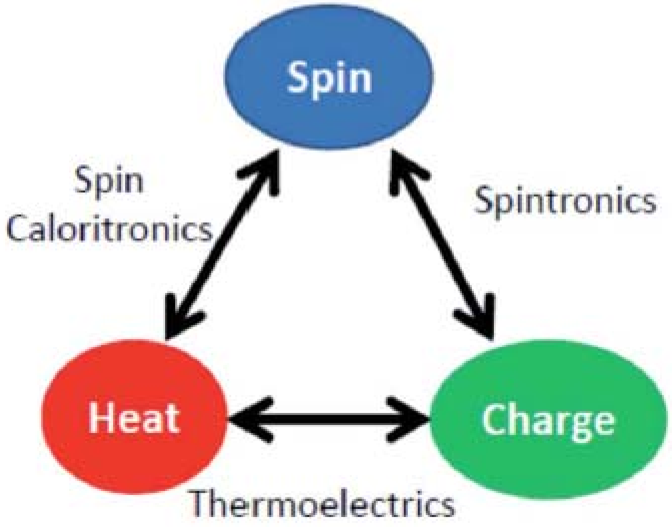
- g~10^{15} W m^{-3} K^{-1} near the peak in the thermal conductivity. (30 times smaller than g for electron-phonon coupling in Au.)
- Does this coupling (and therefore magnon-phonon scattering) determine the thermal conductivity near the peak?
- Is "two temperatures" too crude of a model to capture the physics?

PRB **89**, 024422 (2014)

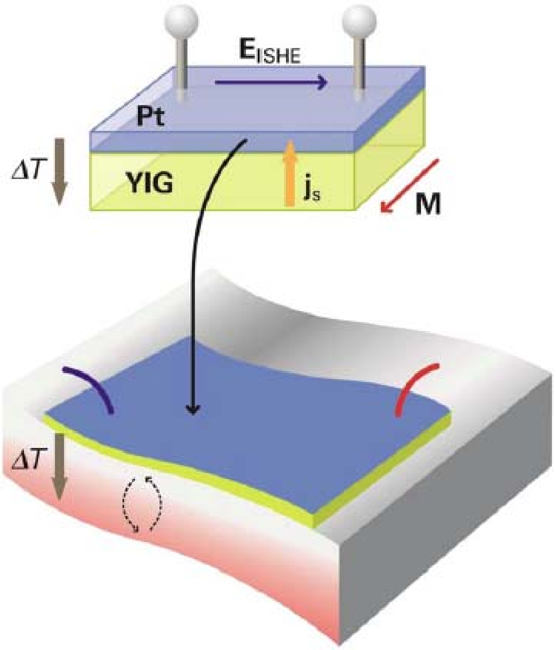


Motivation I: Can we make use of spin in heat engines?

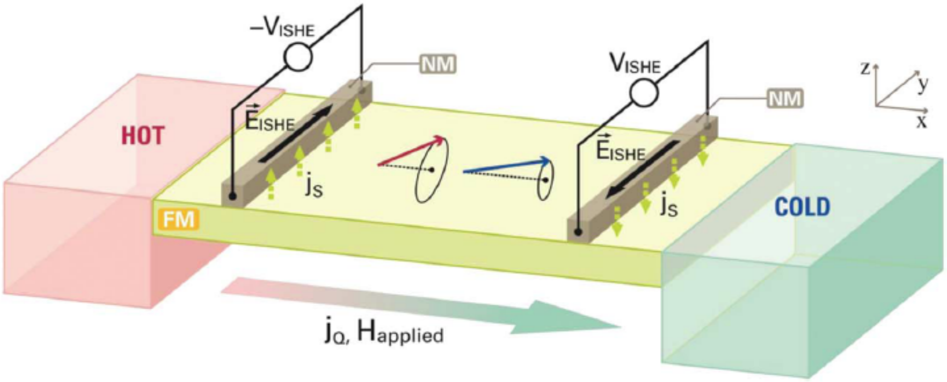
- Electronic states enumerated by energy, wave-vector, spin
- Possible advantages in geometrical scaling, $\nabla E \perp \nabla T$.



Boona, Myers, Heremans, *Energy and Env. Sci*. (2014)



Kirihara *et al*., *Nat. Mat.* (2013)

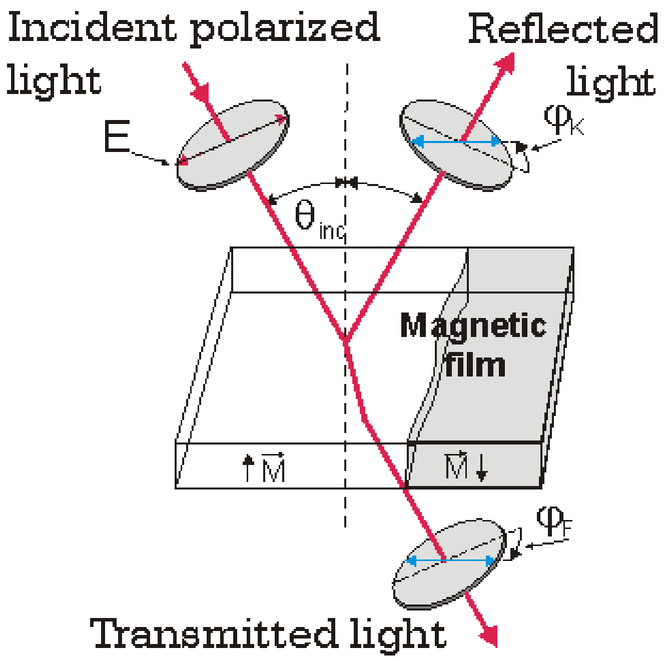


Motivation II: Can we make use of heat currents in information technology?

- Big picture problem: “How can we write magnetic information without resorting to magnetic fields, e.g., with spin currents?”
  - Rapid changes in magnetization and strong temperature gradients in magnetic materials should produce spin currents.
  - Magnitudes of the effects are only beginning to be understood.

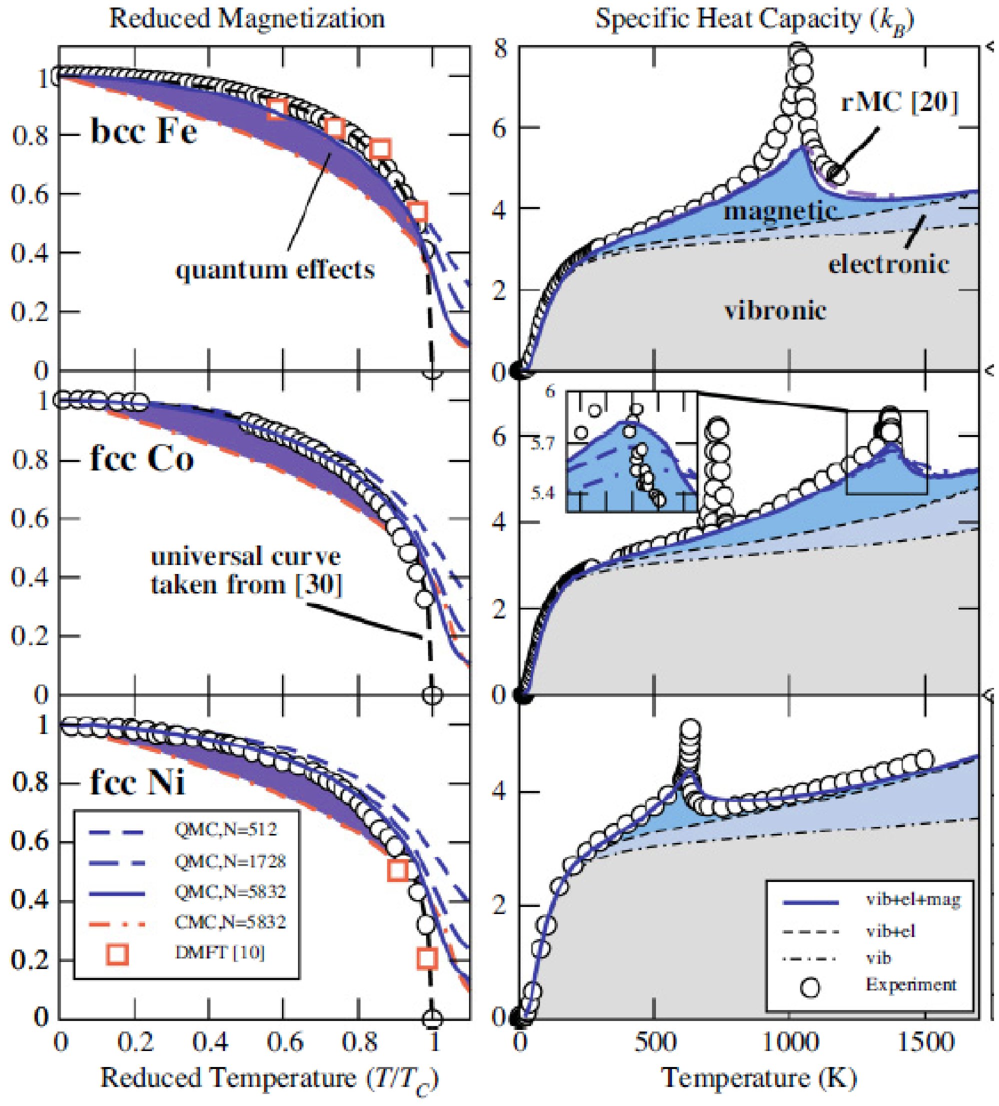
Time-resolved magneto-optic Kerr effect (TR-MOKE) to measure magnetization and spin accumulation

Kerr rotation



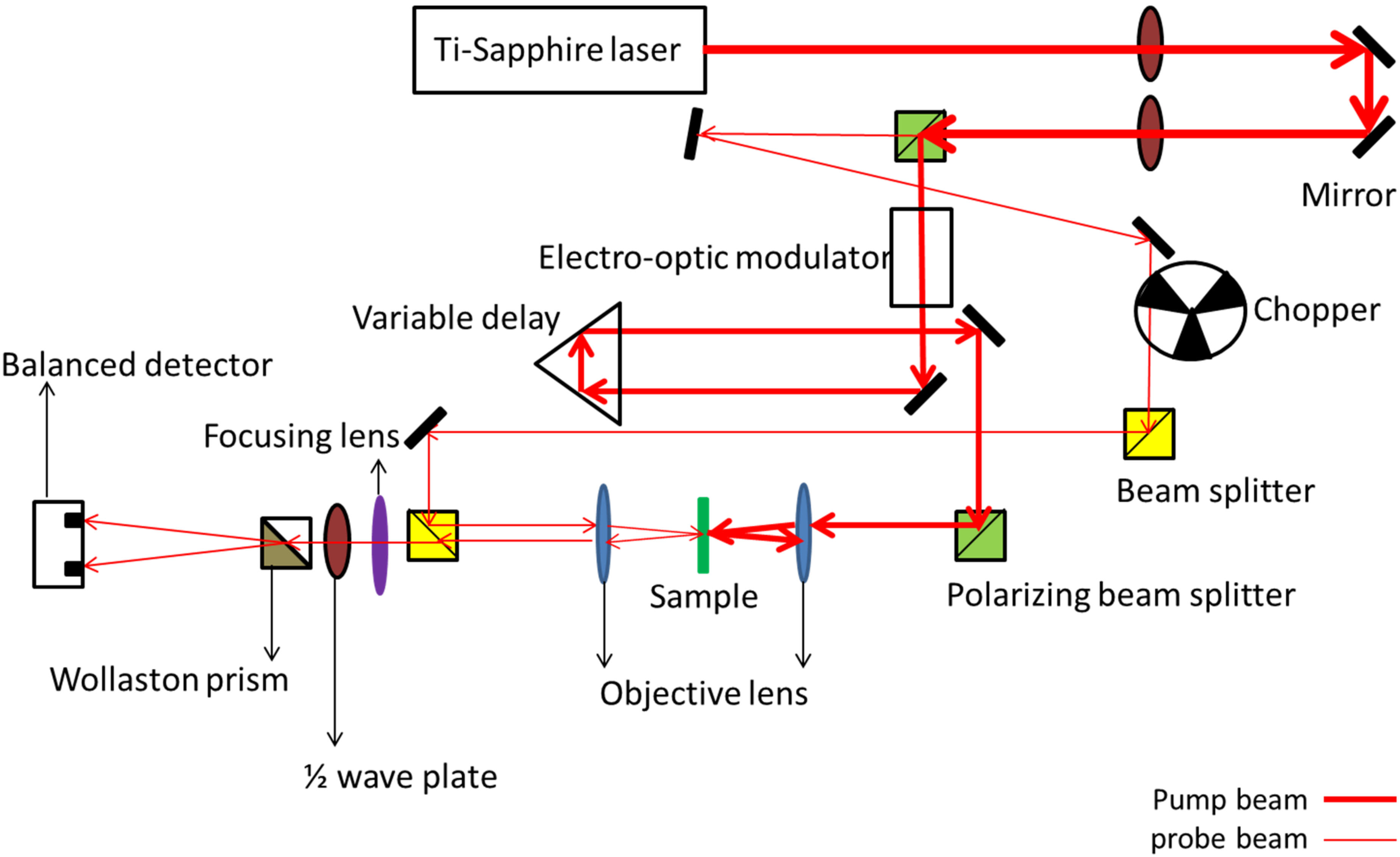
Faraday rotation

http://labfiz.uwb.edu.pl



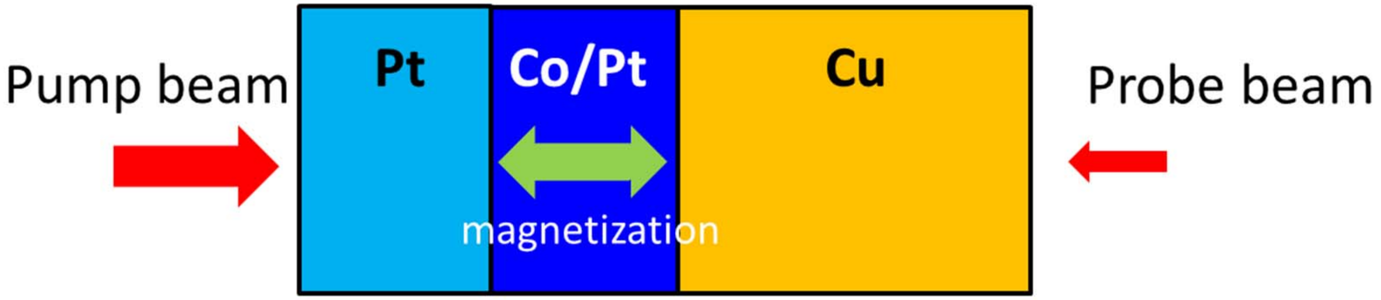
Körmann *et al.*, PRB (2011)

Time-resolved magneto-optic Kerr effect (TR-MOKE) to measure magnetization and spin accumulation

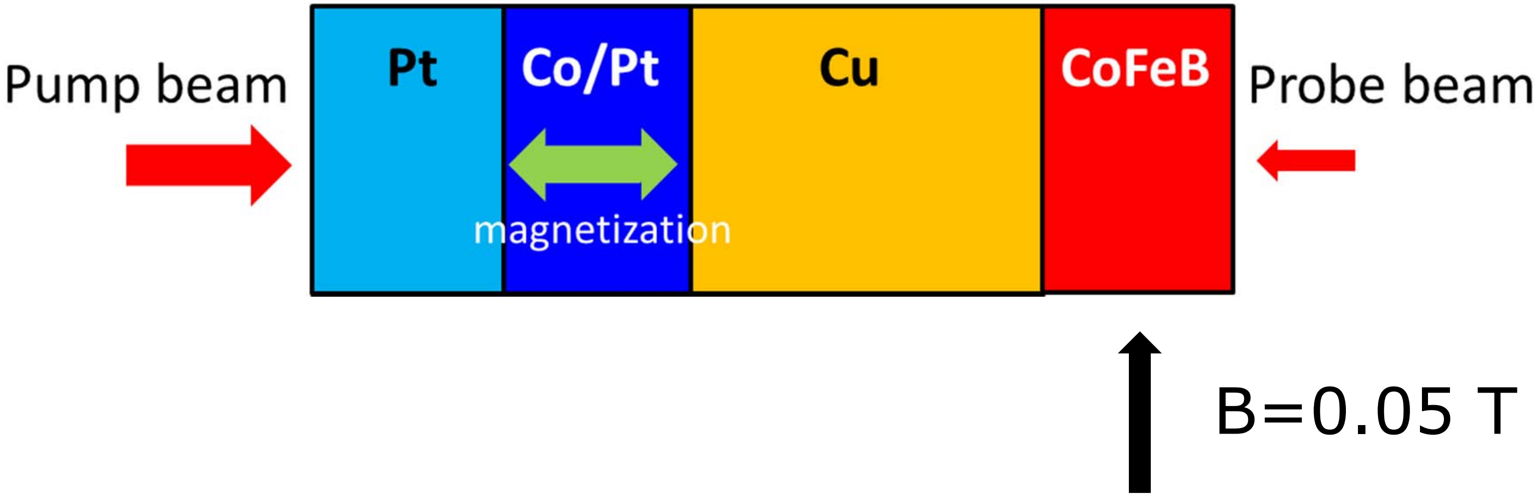


Two types of samples: i) for spin accumulation; and ii) for spin-transfer torque

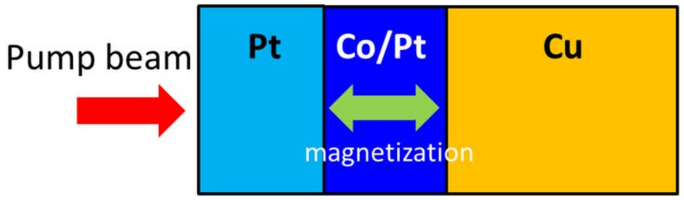
Sapphire/Pt(30)/[Co/Pt]$_{xn}$(6)/Cu(80)/MgO(10)/AlOx(5) (in nm)

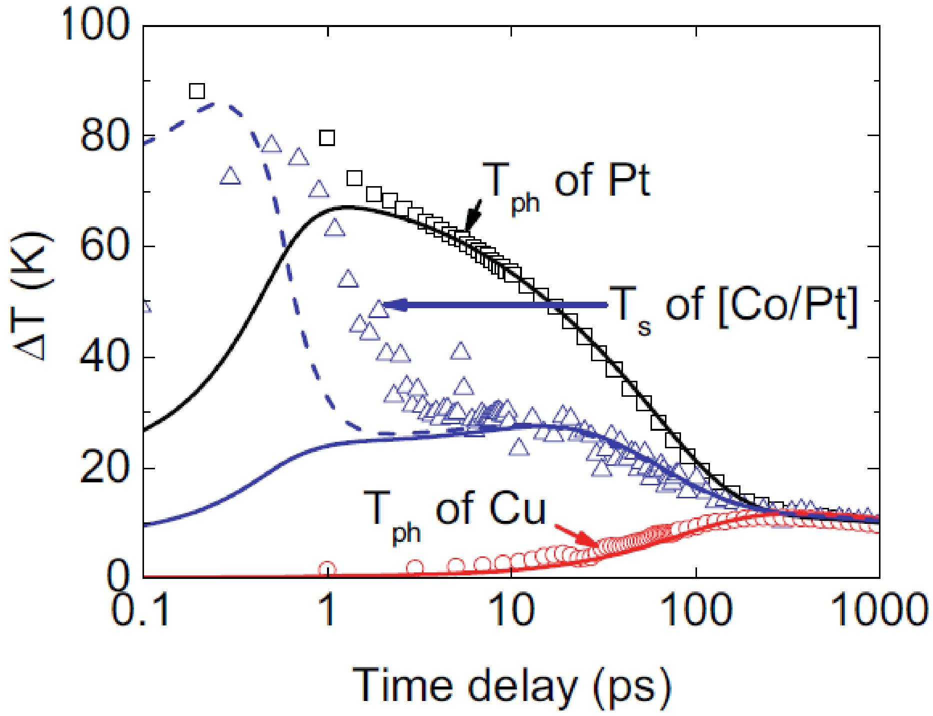


Sapphire/Pt(30)/[Co/Pt]$_{xn}$(6)/Cu(10)/CoFeB(2)/MgO(10)/AlOx(5) (in nm)



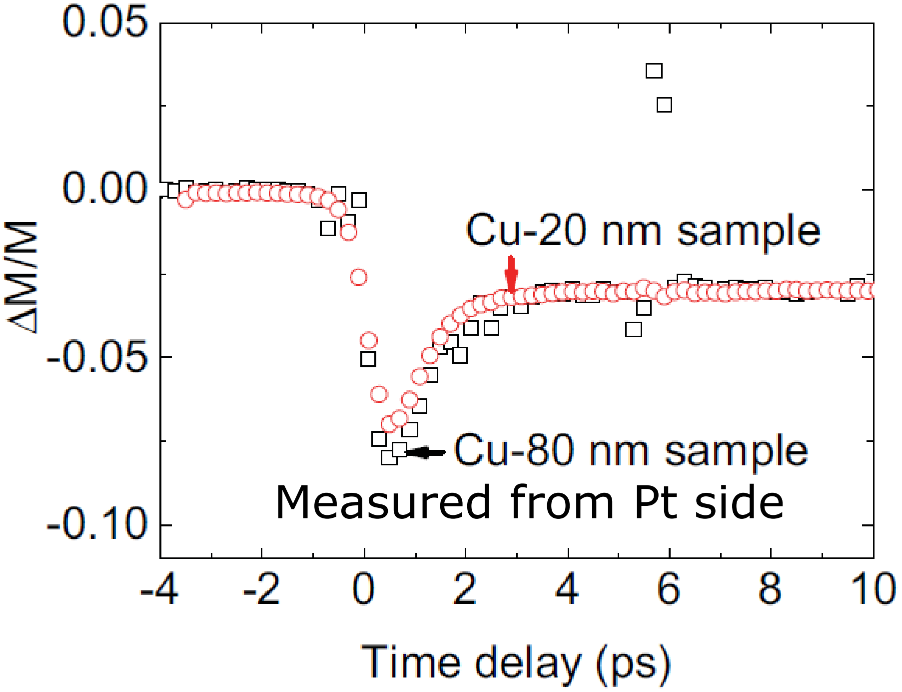
Pump Pt-side, probe either Pt-side or Cu side by either TDTR or TR-MOKE





Normalized Kerr signal from Co/Pt is independent of Cu thickness

$$\left.\frac{\Delta M}{M}\right|_{\max} = -0.08 \pm 0.02 \text{ at } 0.5 \text{ ps}$$



Spin diffusion model

$$\frac{\partial \mu_S}{\partial t} = D\frac{\partial^2 \mu_S}{\partial^2 z} - \frac{\mu_S}{\tau_S}$$

spin generation rate per unit volume

$$G_S = -\frac{dM}{dt}$$

$\mu_S = \mu_\uparrow - \mu_\downarrow$ is the spin chemical potential

D is the spin diffusion constant

τ_S is the spin relaxation time.

	Pt	[Co/Pt]	Cu
D (nm^2/ps)	200	100	6500
τ_s (ps)	0.5	0.05	25
$(D\tau_s)^{1/2}$ (nm)	10	2.2	400

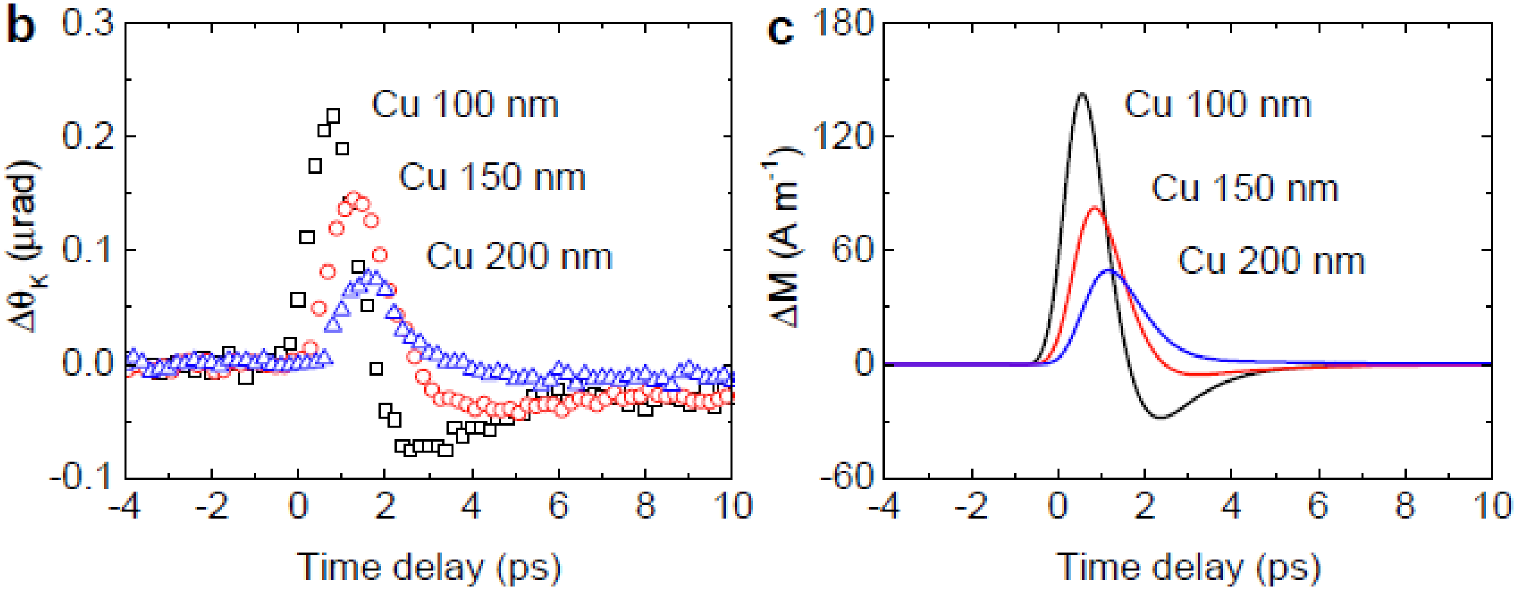
Comparison between experiment and spin diffusion model using spin generation = *dM/dt*

Measured Kerr signal on Cu side

E=36 J m^{-2}

Spin diffusion model

E=17 J m^{-2}



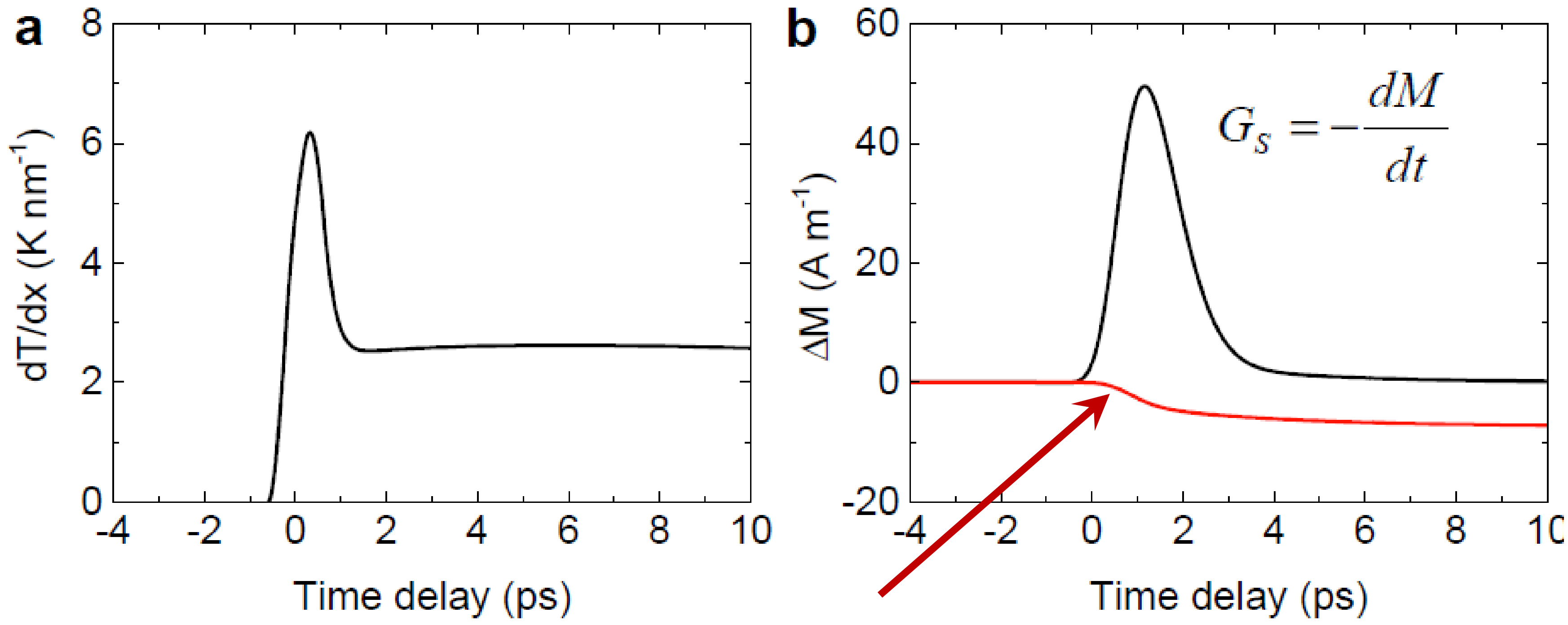
- No prior studies of how to convert Kerr rotation to spin accumulation.
- Working in progress to relate Kerr rotation quantitatively to spin accumulation in Cu and Au.

Temperature gradient also contributes to spin accumulation

$$J_S = -\frac{\mu_B}{e}\left(\sigma_\uparrow S_\uparrow - \sigma_\downarrow S_\downarrow\right)\nabla T = -\frac{\mu_B}{e}\frac{\sigma_\uparrow S_\uparrow - \sigma_\downarrow S_\downarrow}{\sigma_\uparrow + \sigma_\downarrow}\sigma\nabla T$$

Temperature gradient in the Pt/Co layer from thermal modeling

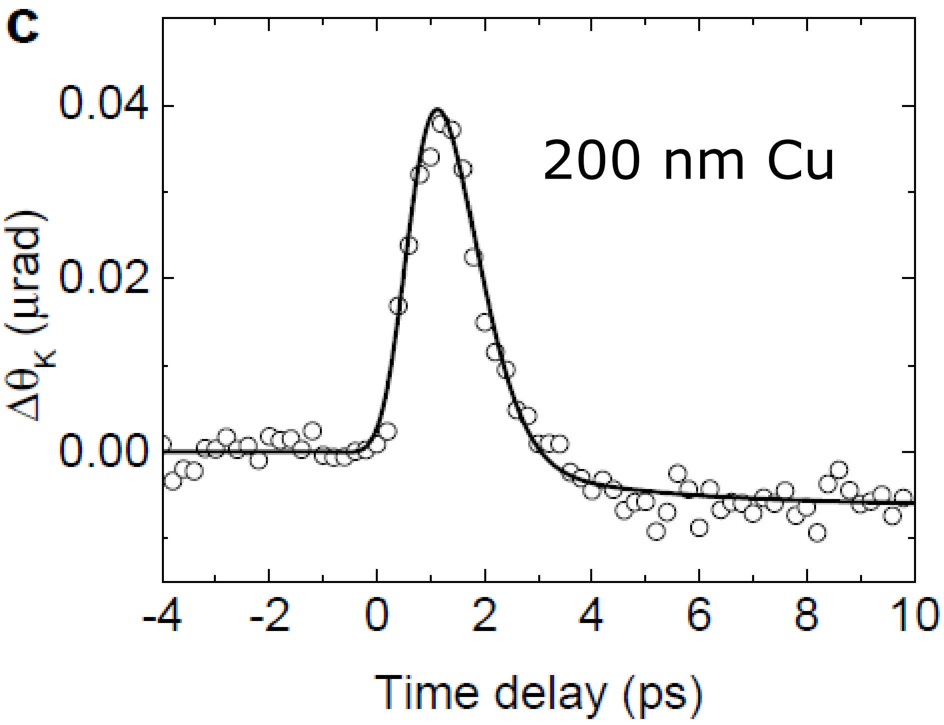
Calculated spin accumulations



$$\frac{\sigma_\uparrow S_\uparrow - \sigma_\downarrow S_\downarrow}{\sigma_\uparrow + \sigma_\downarrow} \approx 5\ \mu\mathrm{V\,K^{-1}}$$

Temperature gradient also contributes to spin accumulation

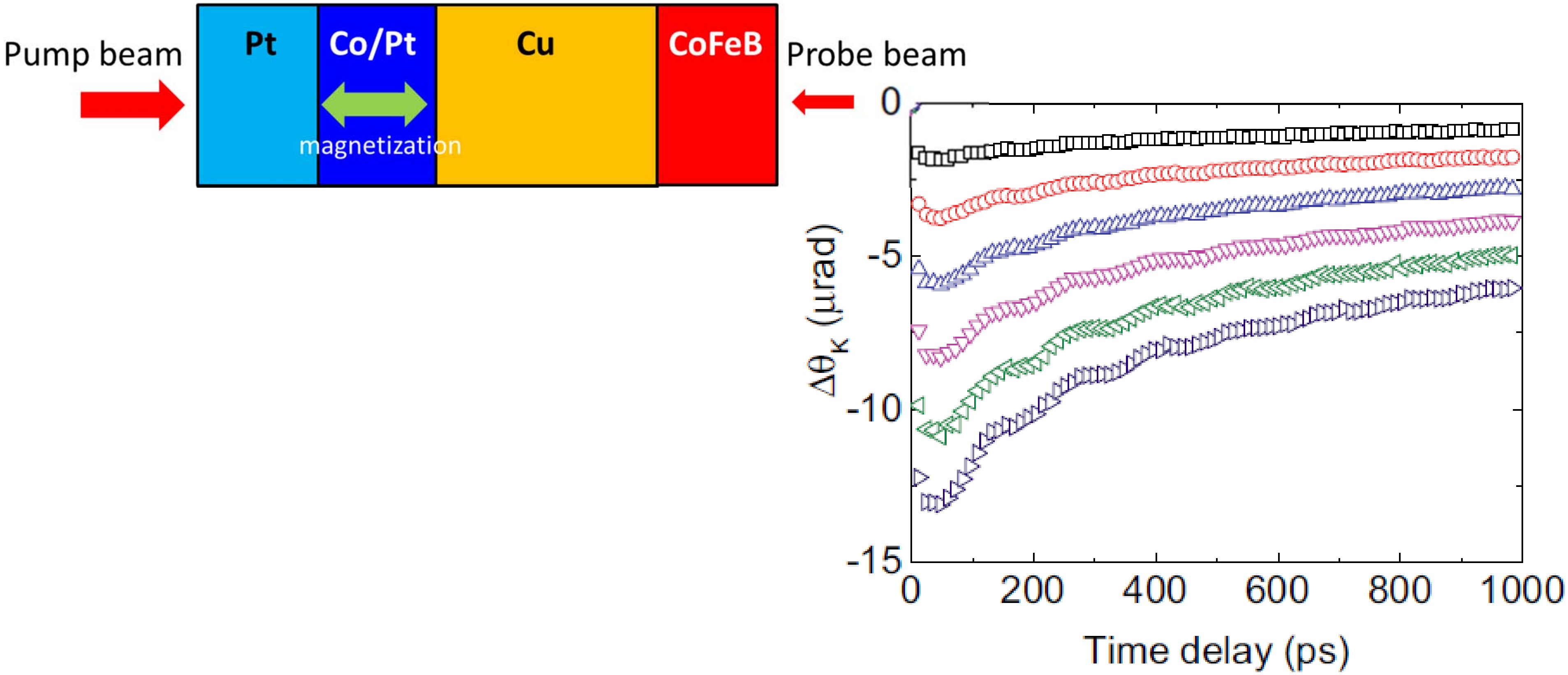
- More refined data with comparison to spin diffusion model including the spin-dependent Seebeck effect
- Comparison between model and data gives



$$\left.\frac{\Delta\theta_K}{\Delta M}\right|_{Cu} \approx 8.5\times10^{-10}\ \text{rad m A}^{-1}$$

Use an in-plane magnetic layer of CoFeB to calibrate the magnitude of the spin current

- Spin current kicks magnetization of CoFeB out-of-plane (spin torque) and induces precession.
- Amplitude of the precession can be calibrated using Kerr rotation in a static field perpendicular field.



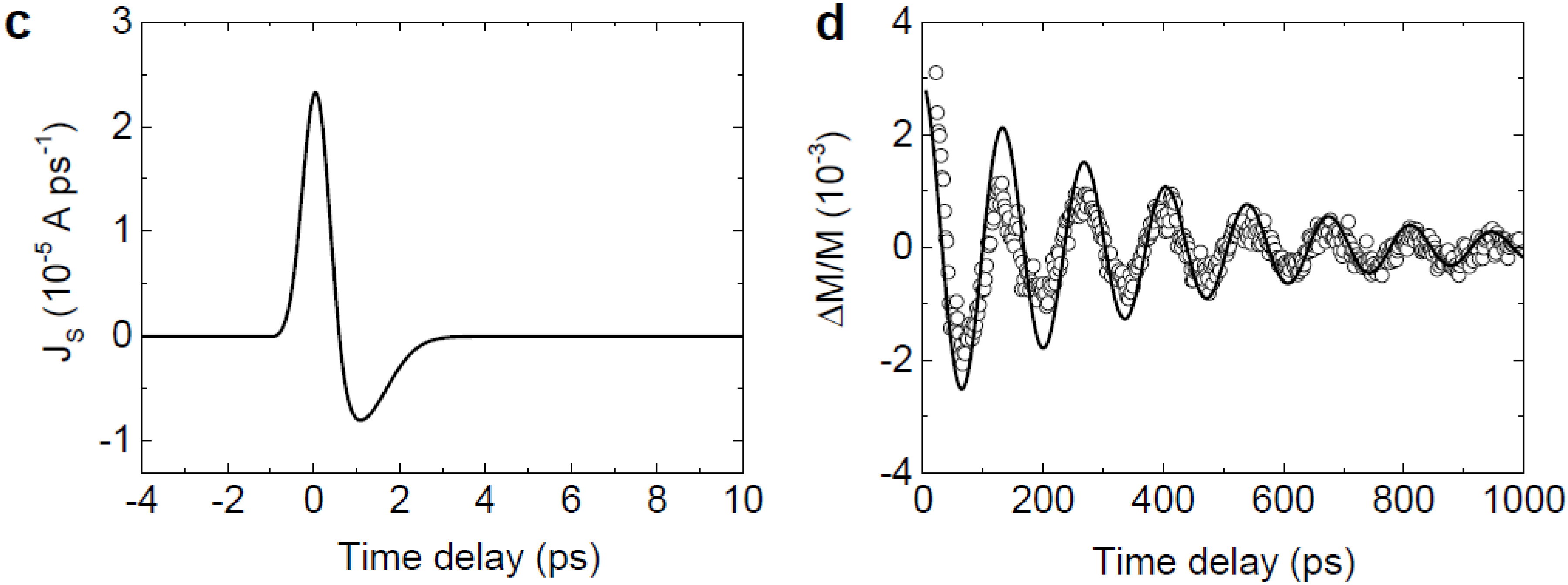
Combine spin diffusion model with magnetization dynamics

- Spin current has transverse polarization with respect to CoFeB magnetization, therefore, CoFeB is a perfect sink for spin (spin chemical potential is zero at Cu/CoFeB interface)
- Cu layer is thin, therefore, we need to include finite spin conductance at the [Co/Pt]/Cu and Cu/CoFeB interfaces
  - longitudinal spin conductance $\frac{G_{\uparrow} + G_{\downarrow}}{2e^2} \approx 0.4\text{x}10^{15}\ \Omega^{-1}\ \text{m}^{-2}$
  - transverse spin conductance $\frac{\mathrm{Re}\{G_{\uparrow\downarrow}\}}{e^2} \approx 0.6\text{x}10^{15}\ \Omega^{-1}\ \text{m}^{-2}$

Good agreement between predicted and measured amplitude of spin precession

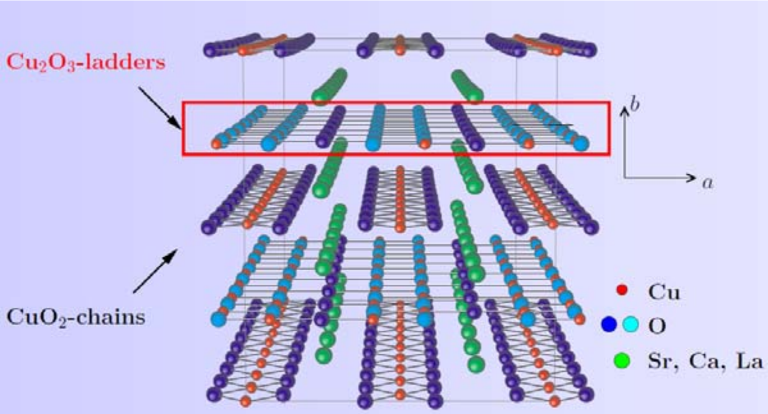
Landau-Lifshitz-Gilbert equation

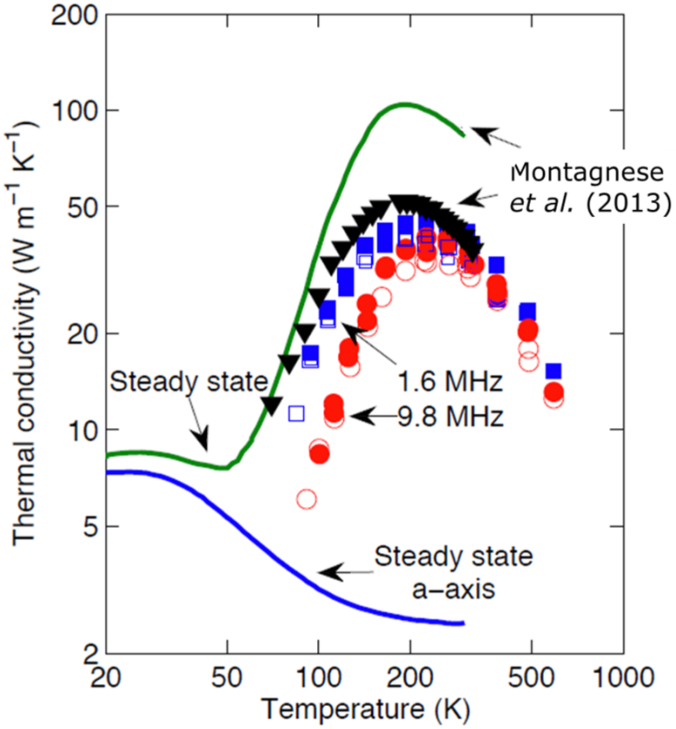
$$\dot{m} = -\gamma\, m \times H_{eff} + \alpha\, m \times \dot{m} + \frac{J_S}{M_S h} m \times \left(m \times m_{fixed} \right)$$



Summary

- Time-domain thermoreflectance (TDTR) with MHz thermal waves enables probing of non-equilibrium between magnons and phonons on sub-micron length scales.
- Two-temperature model gives magnon-phonon coupling parameter g~10^{15} W m^{-3} K^{-1} at the peak in the thermal conductivity.
- But is a two-temperature model a reasonable approximation to reality?





Summary

- Picosecond demagnetization of [Co/Pt] multilayer produces spin-currents that can exert a spin-transfer torque on a in-plane magnetic layer or produce spin accumulation in Cu
  - 6% of loss of demagnetization of [Co/Pt] magnetization is transferred to CoFeB layer
  - Increase efficiency with [Co/Pd] or [Co/Ni] with longer spin diffusion length?
- Experiments and modeling give a spin-dependent Seebeck effect in [Co/Pt] of ≈5 μV K^{-1}
  - Will a tunnel barrier produce a larger effect?