Bulk and interfacial thermal transport by electrons, phonons, and magnons
(in the context of normal-metal/YIG bilayers)

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I-MRSEC

Separate the transport coefficients by the power of the length scale in the denominator.

- Conventional heat currents, e.g., heat diffusion equation, Fourier's law in steady-state governed by thermal conductivity Λ

$$J_Q = -\Lambda \nabla T \qquad \Lambda \propto \mathrm{W\ m^{-1}\ K^{-1}}$$

- Interface thermal conductance *G*, ΔT=temperature across an interface

$$J_Q = G \Delta T \qquad G \propto \mathrm{W\ m^{-2}\ K^{-1}}$$

- Volumetric heat currents exchanged between excitation, e.g., two-temperature model of electrons and phonons, electron-phonon coupling parameter g_{ep}

$$j_Q = g_{ep}(T_e - T_p) \quad g_{ep} \propto \mathrm{W\ m^{-3}\ K^{-1}}$$

10 transport coefficients for normal-metal/YIG bilayer

- Normal metal (NM): Λ_p, Λ_e, g_{ep}
- YIG: Λ_p, Λ_m, g_{mp}
- Interface: (first index is the normal metal) G_{pp}, G_{ep}, G_{em}, G_{pm}

10 transport coefficients for normal-metal/YIG bilayer

- Au: $\Lambda_p,\ \Lambda_e,\ g_{ep}$
- YIG: $\Lambda_p,\ \Lambda_m,\ g_{mp}$
- Interface: (first index is the normal metal) $G_{pp},\ G_{ep},\ G_{em},\ G_{pm}$

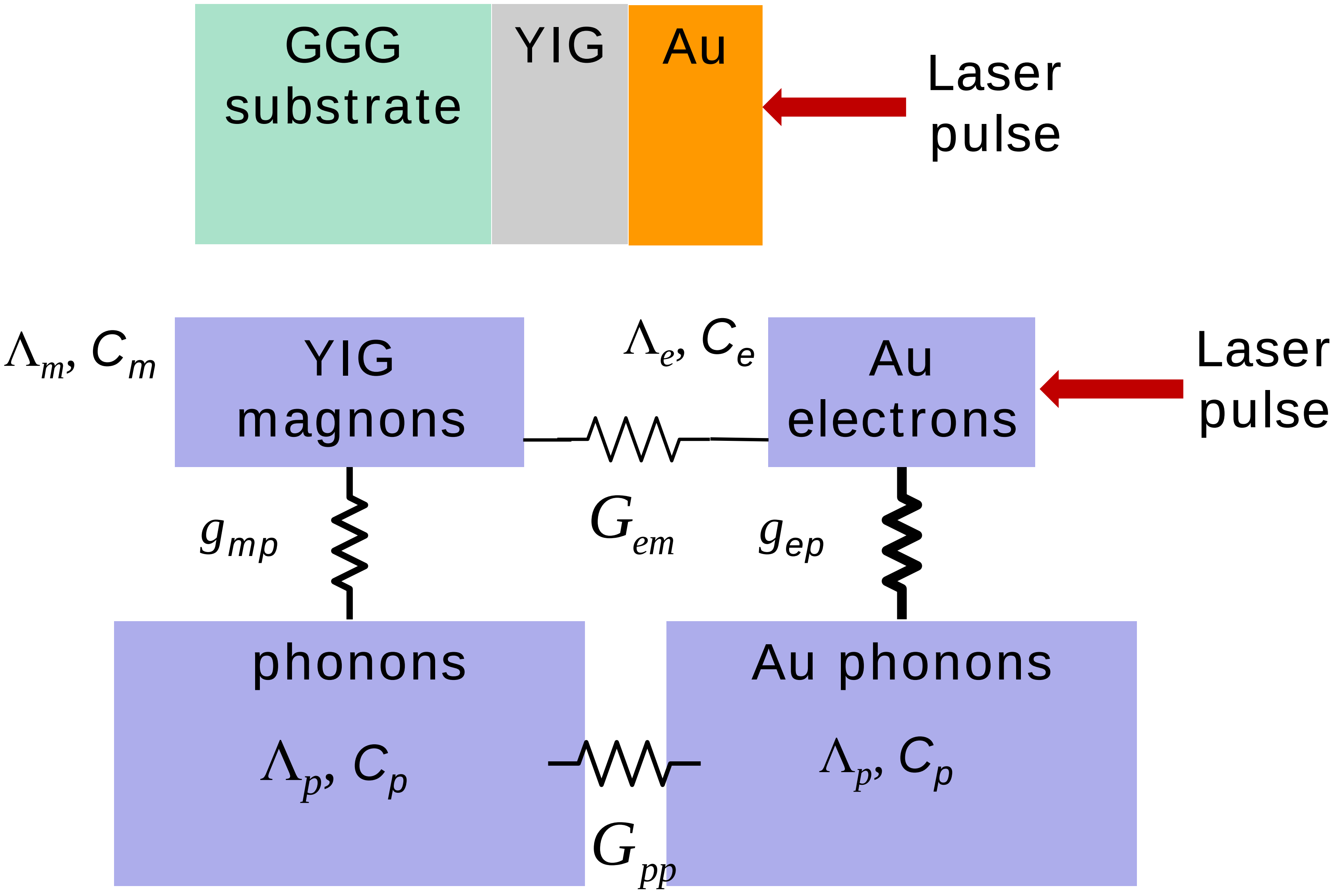
well understood

poorly understood and important

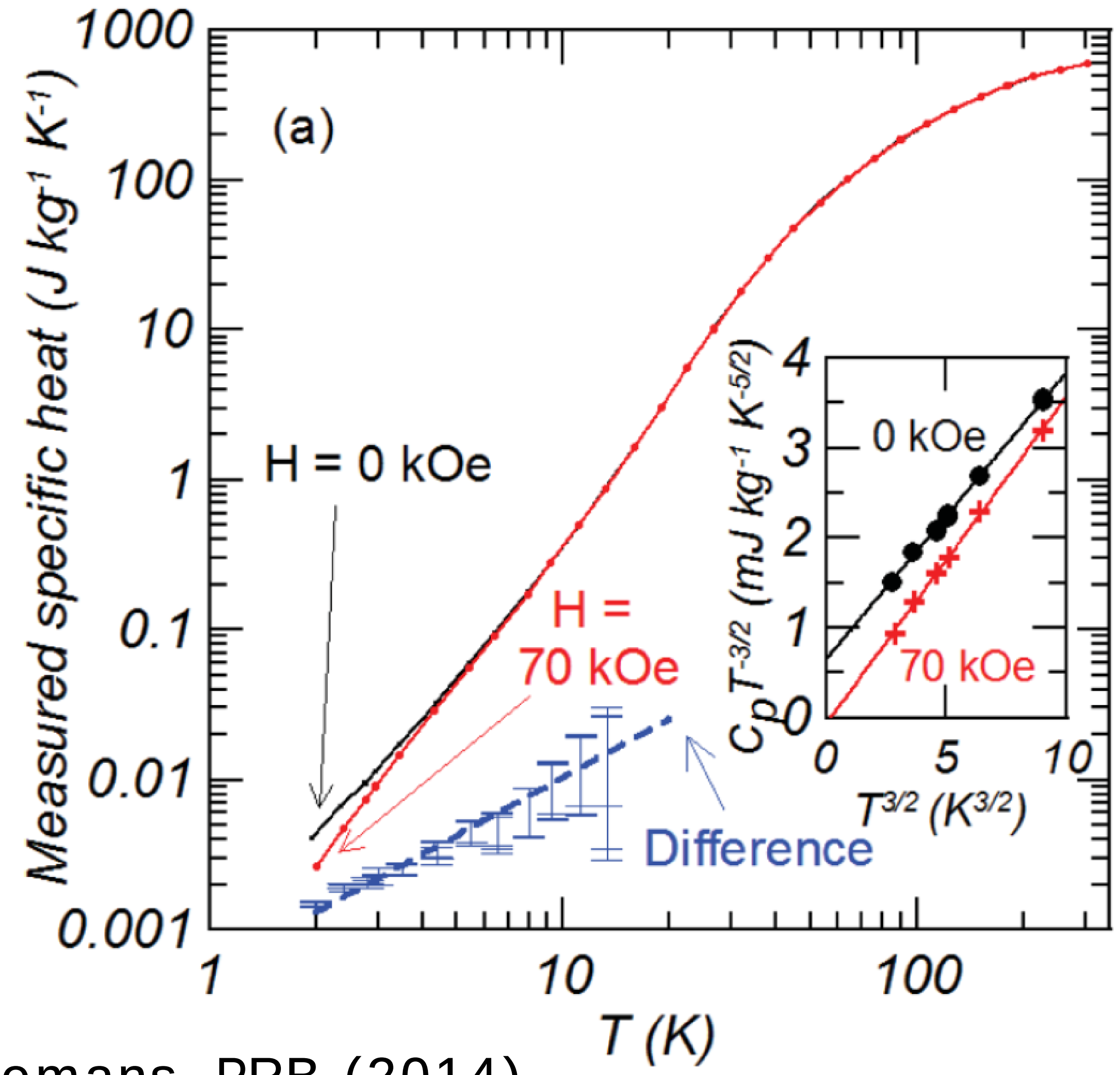
$G_{pm} < G_{em}$

$G_{ep} < G_{pp}$

Thermal circuit for picosecond spin Seebeck effect



Heat capacities are dominated by phonons



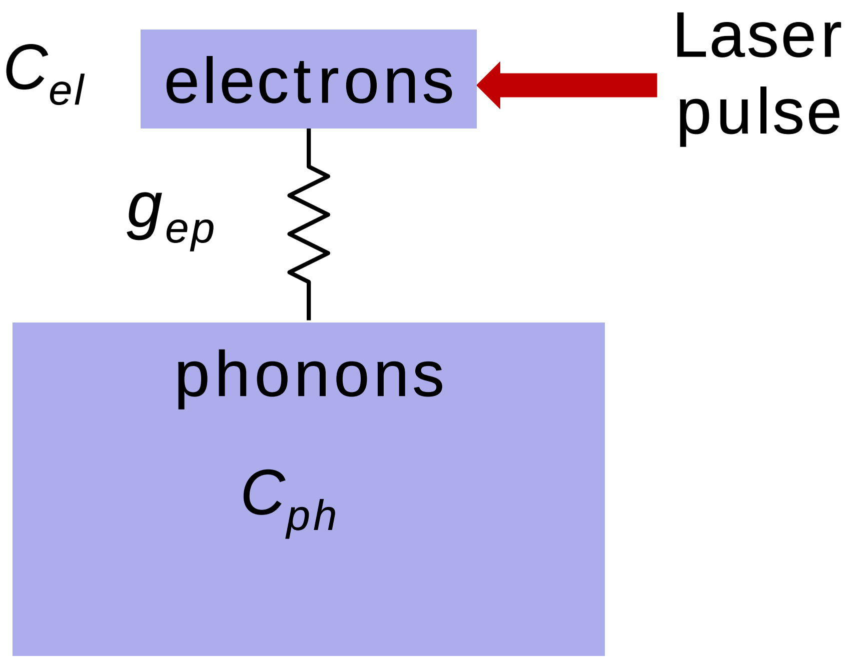
Boona and Heremans, PRB (2014)

Many experiments on SSE take place on long time scales where we do not need to care about heat capacities of anything except the phonons

- Long time-scale compared to what? Let's focus on behavior near room temperature and first consider the normal-metal (NM).

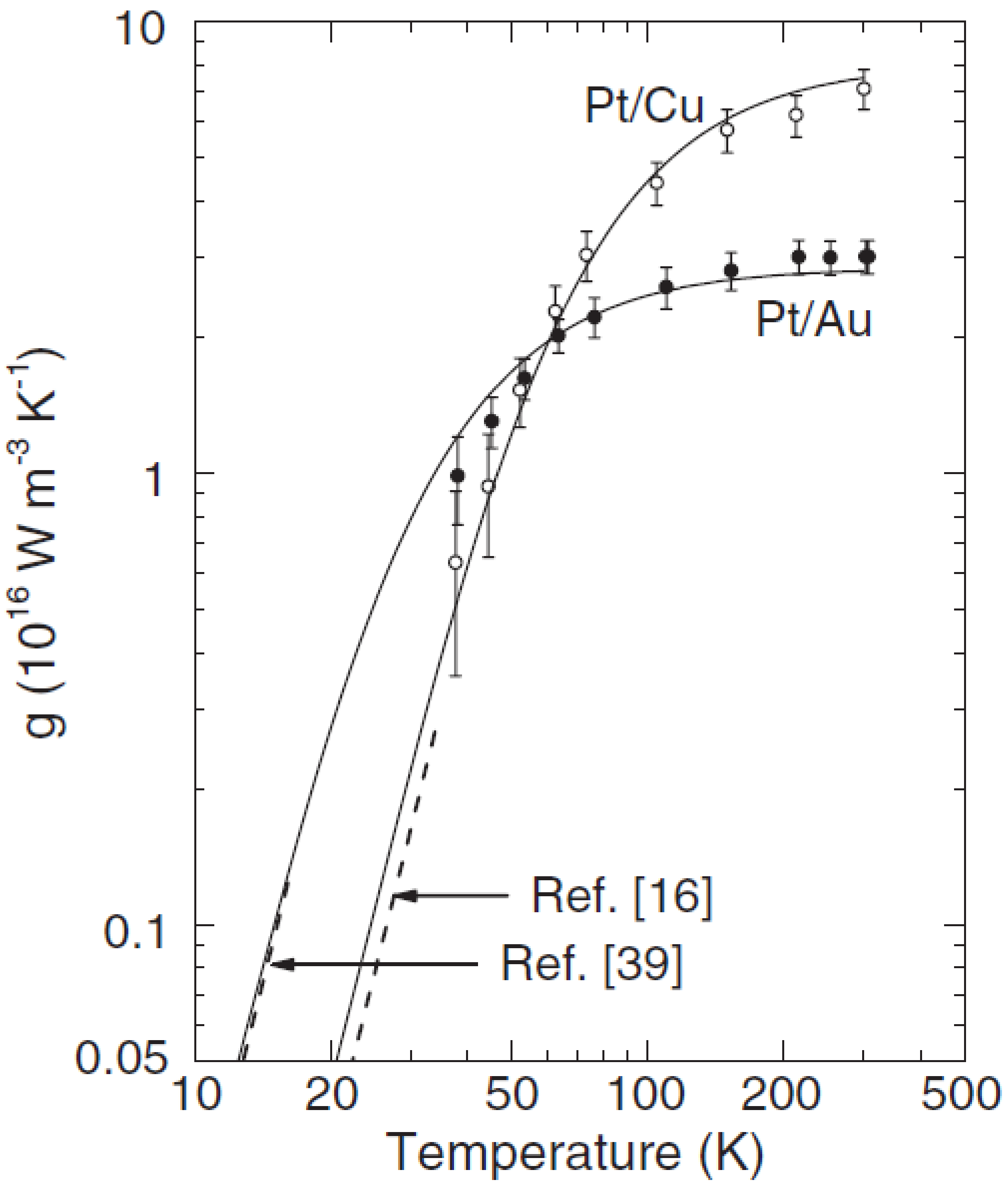
$$\tau \approx \frac{C_{el}}{g_{ep}} \sim \frac{3\times 10^{4}\ \mathrm{J\ m^{-3}\ K^{-1}}}{10^{17}\ \mathrm{W\ m^{-3}\ K^{-1}}} \sim 300\ \mathrm{fs}$$

$$0.1 \le \tau \le 1\ \mathrm{ps}$$



Near-equilibrium measurements using Pt as a thermostat for the electrons in Au and Cu

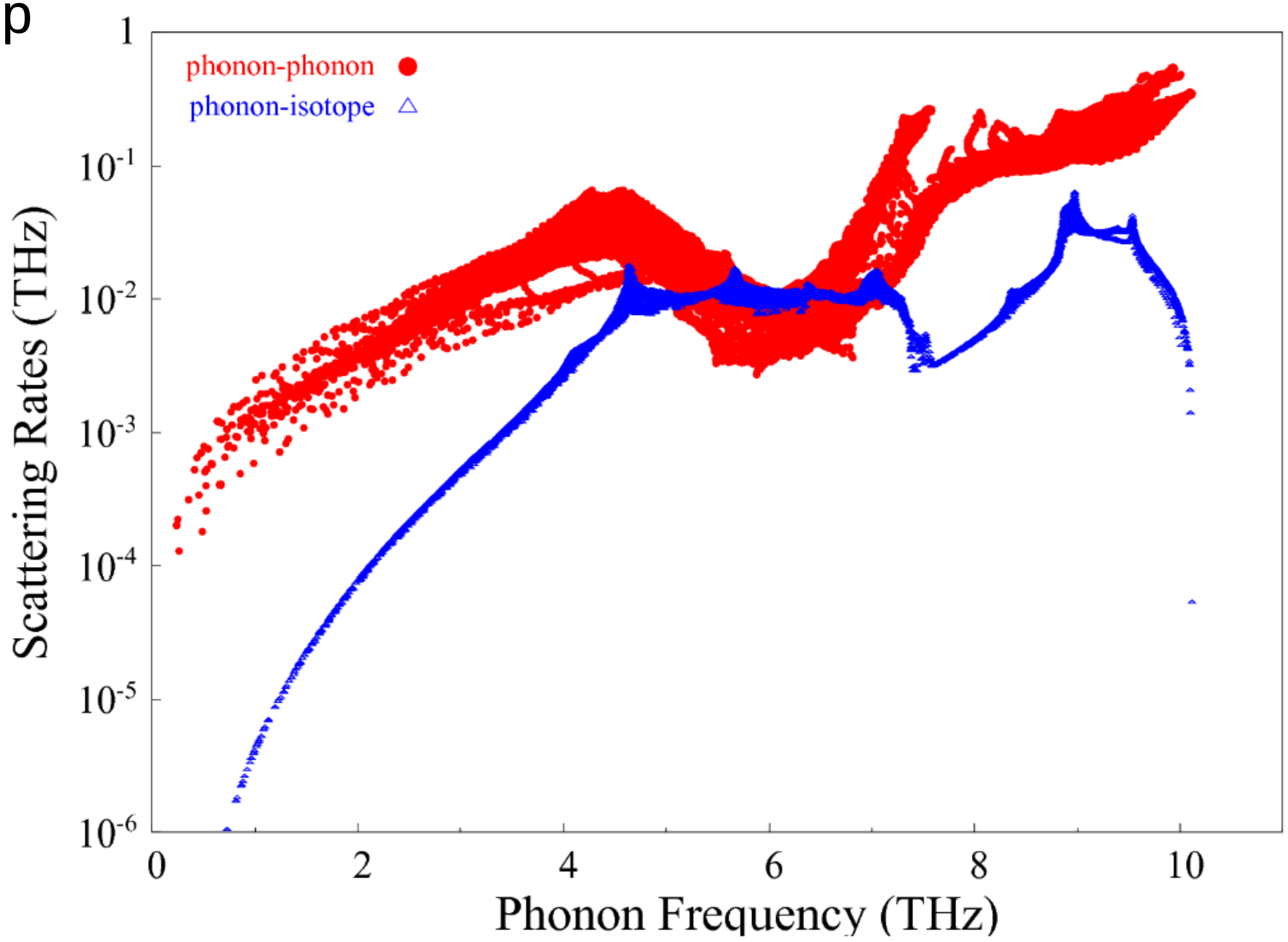
- Solid lines are the predictions of the original Kaganov “two-temperature” model of 1957
- Dashed lines are T^4 extrapolations of low temperature physics experiments.



Wang and Cahill, PRL (2012)

Phonon-phonon interactions have been heavily studied in the context of phonon thermal conductivity

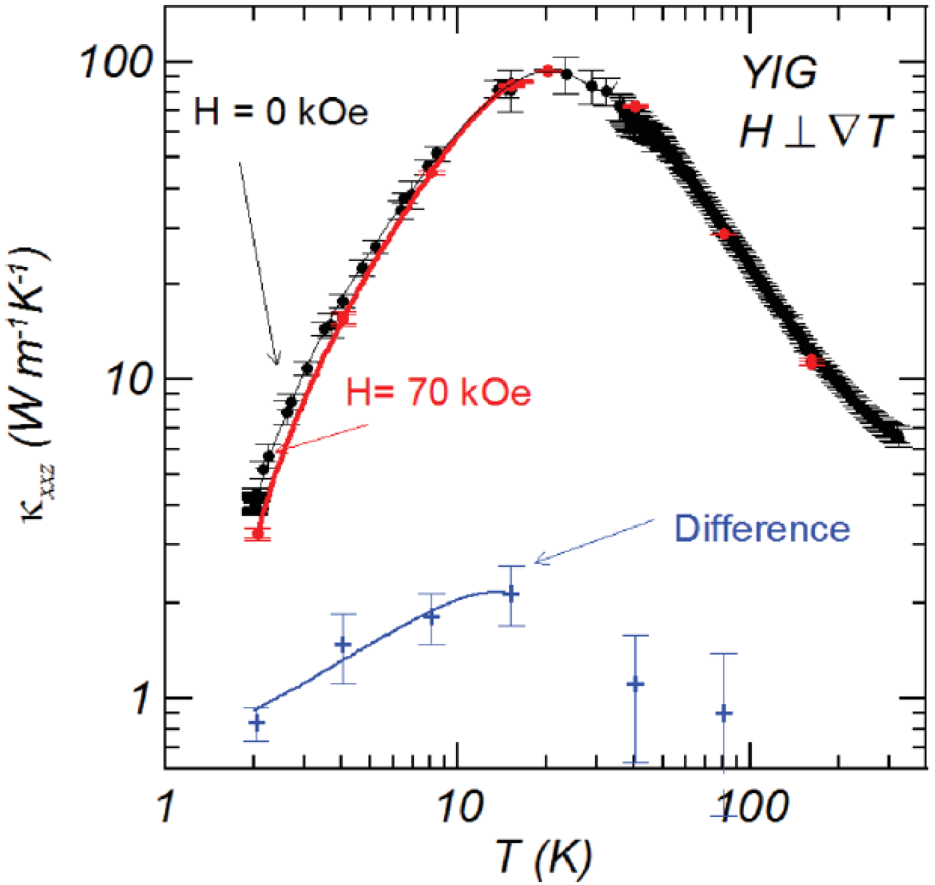
- Example of acoustic phonon lifetimes for GaN calculated by David Broido's group



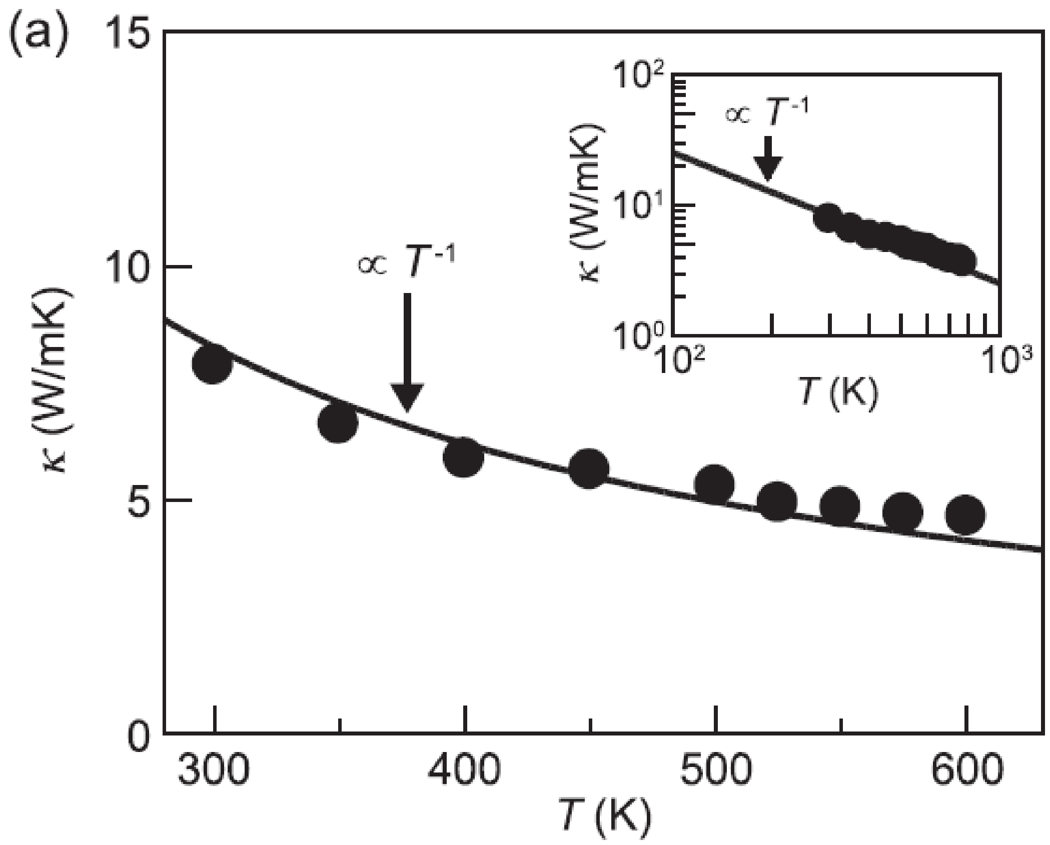
Zheng *et al.*, supplement to PRM (2019)

Magnon thermal conductivity of YIG is small compared to phonons

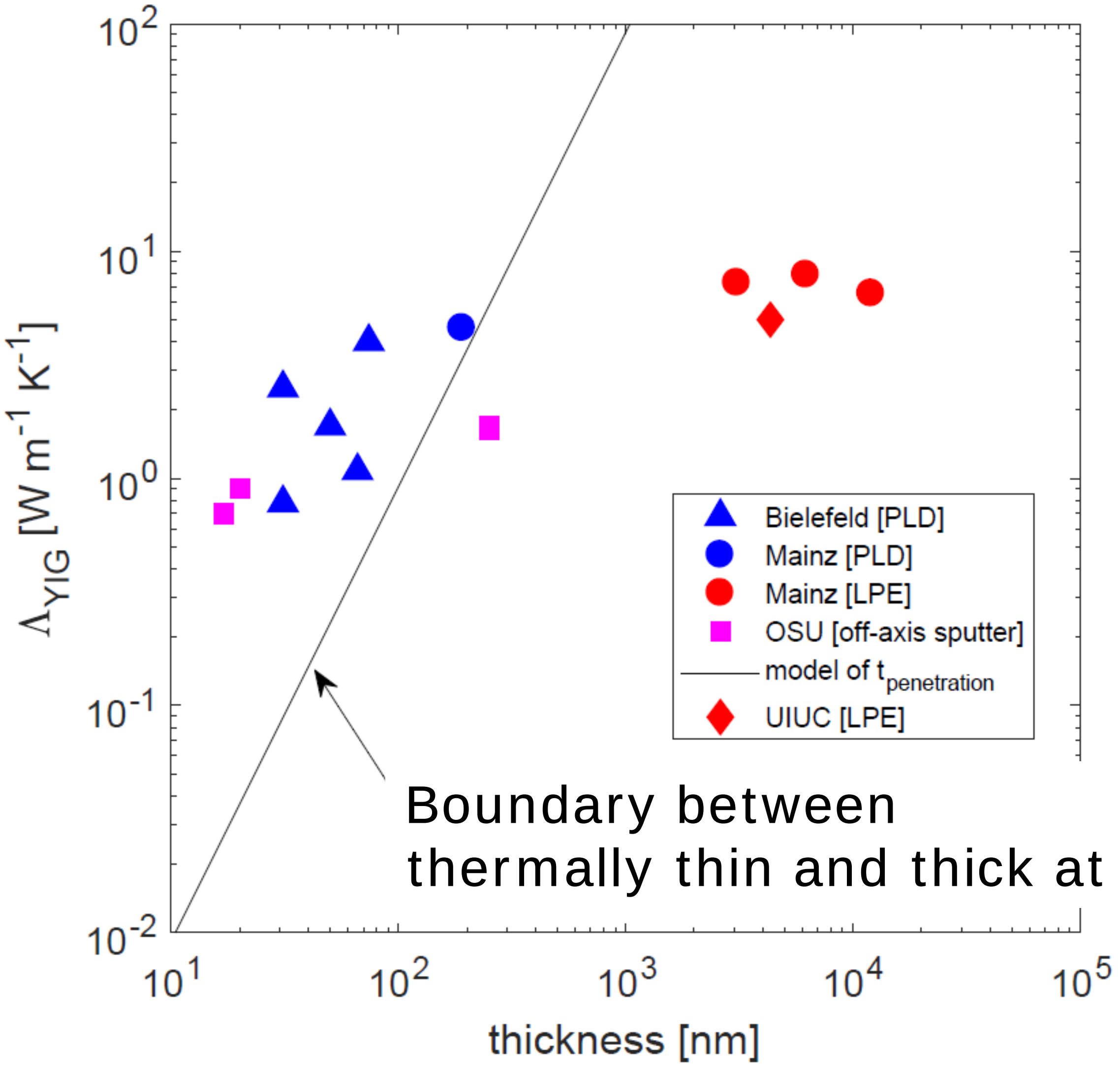
Boona and Heremans, PRB (2014)



Uchida *et al.*, PRX (2014)



Reduction of phonon thermal conductivity by disorder in YIG films deposited by off-axis sputtering and pulsed laser deposition

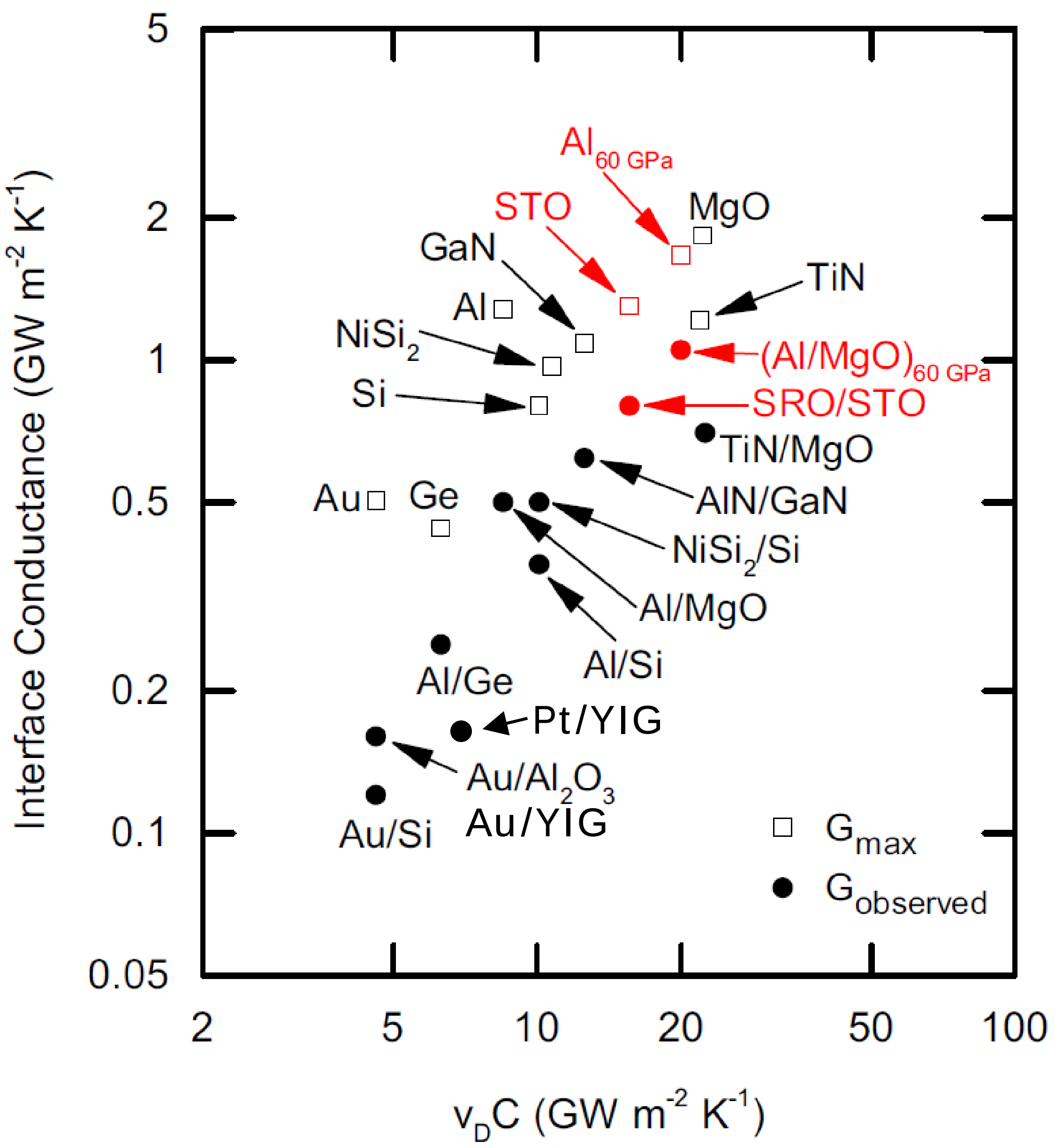


Boundary between
thermally thin and thick at 10 MHz

Pek, unpublished

Phonon mediated interface thermal conductance is (mostly) understood

- Au/YIG and Pt/YIG added to compilation of data (mostly from my group) for clean interfaces at room temperature.



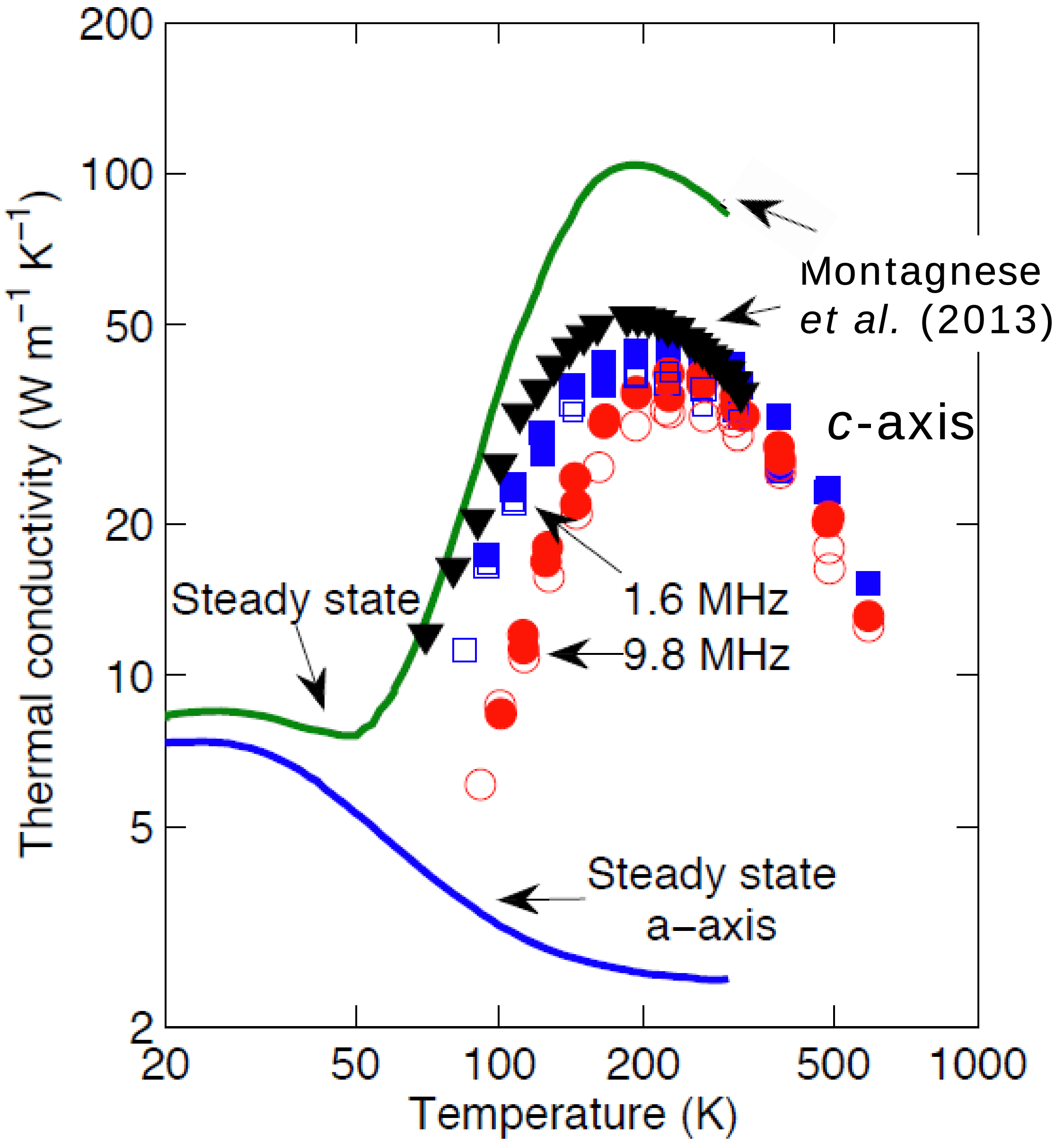
Wilson *et al*., PRB (2015)

Magnon-magnon and magnon-phonon thermalization is much less studied

- Not clear to me how to carry-out a time-domain measurement of relaxation of thermal magnons in YIG (?)
- Gilbert damping is a magnon-magnon scattering process (?); therefore, it is difficult to draw insight from an extrapolation of Gilbert damping to high frequencies for the equilibration of magnons and phonons.
- How can we know if the two-temperature framework for energy exchange between magnons and phonons is a good approximation?

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

- An example where we do not directly access the time-scale of the magnon-phonon thermalization but we use high frequencies to observe the finite thermal conductance of coupling phonons to magnons.
- This approach is limited to $\Lambda_m > \Lambda_p$



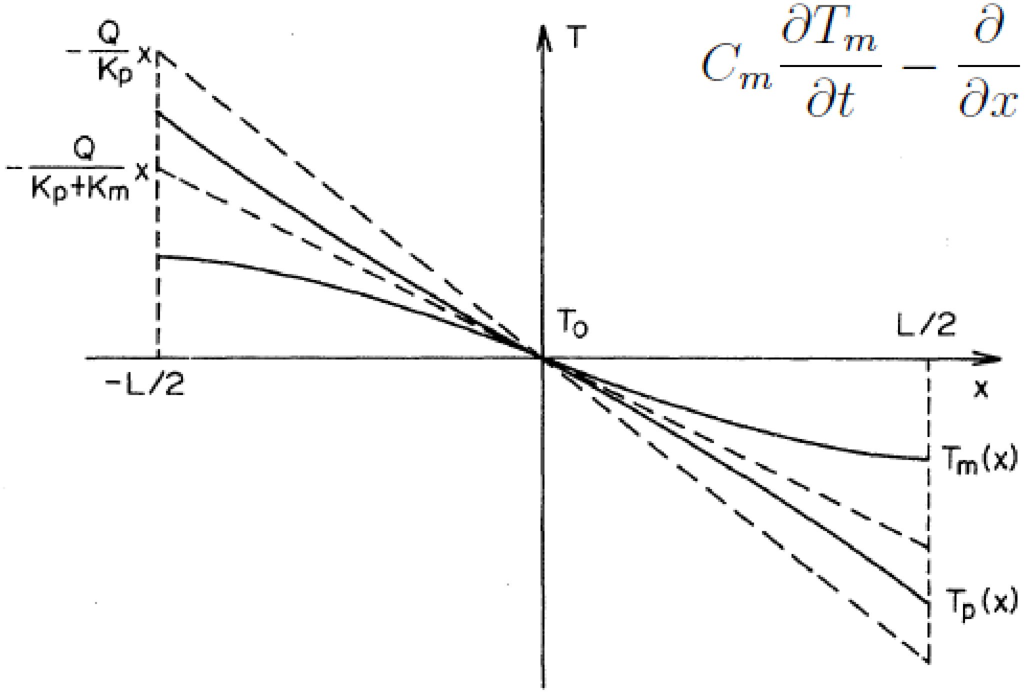
Hohensee *et al*., PRB (2014)

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.

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

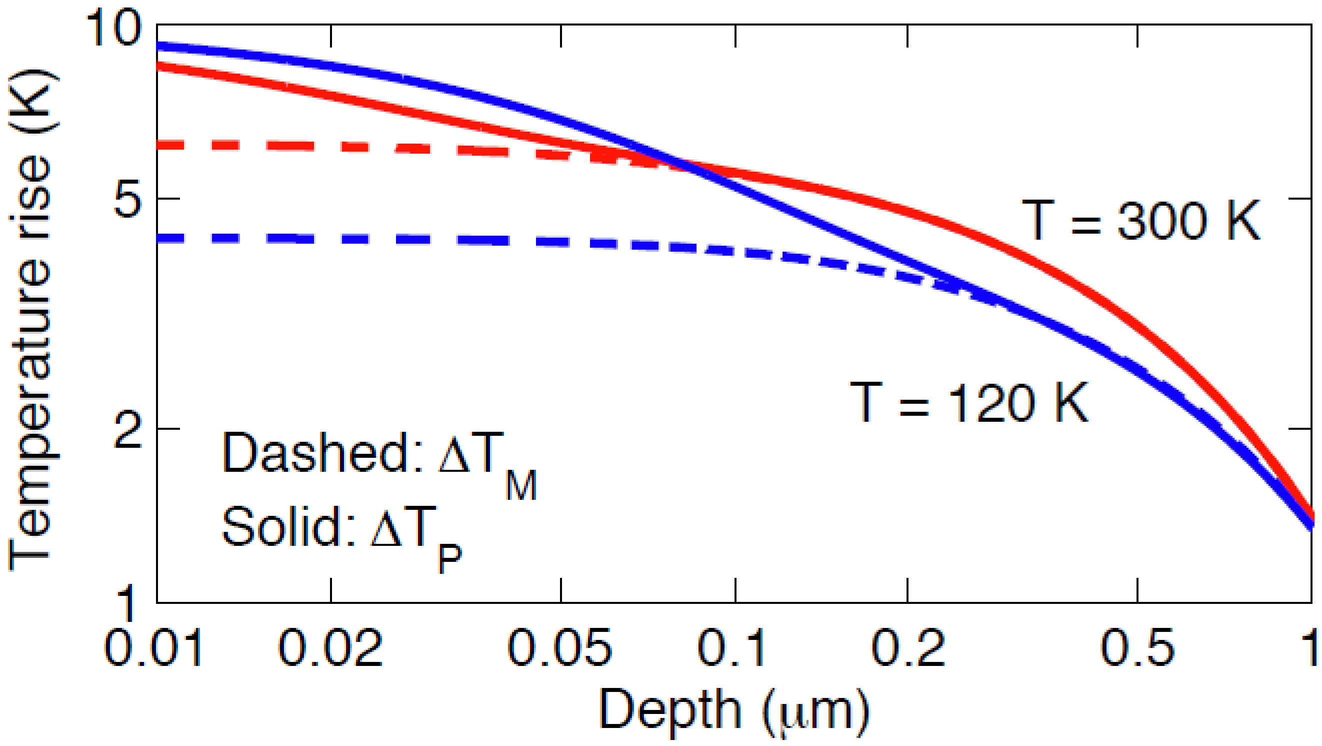
$$C_m \frac{\partial T_m}{\partial t} - \frac{\partial}{\partial x}\left(\Lambda_m \frac{\partial T_m}{\partial x}\right) + g(T_m - T_p) = 0.$$



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

Use a two-channel model: magnons and phonons

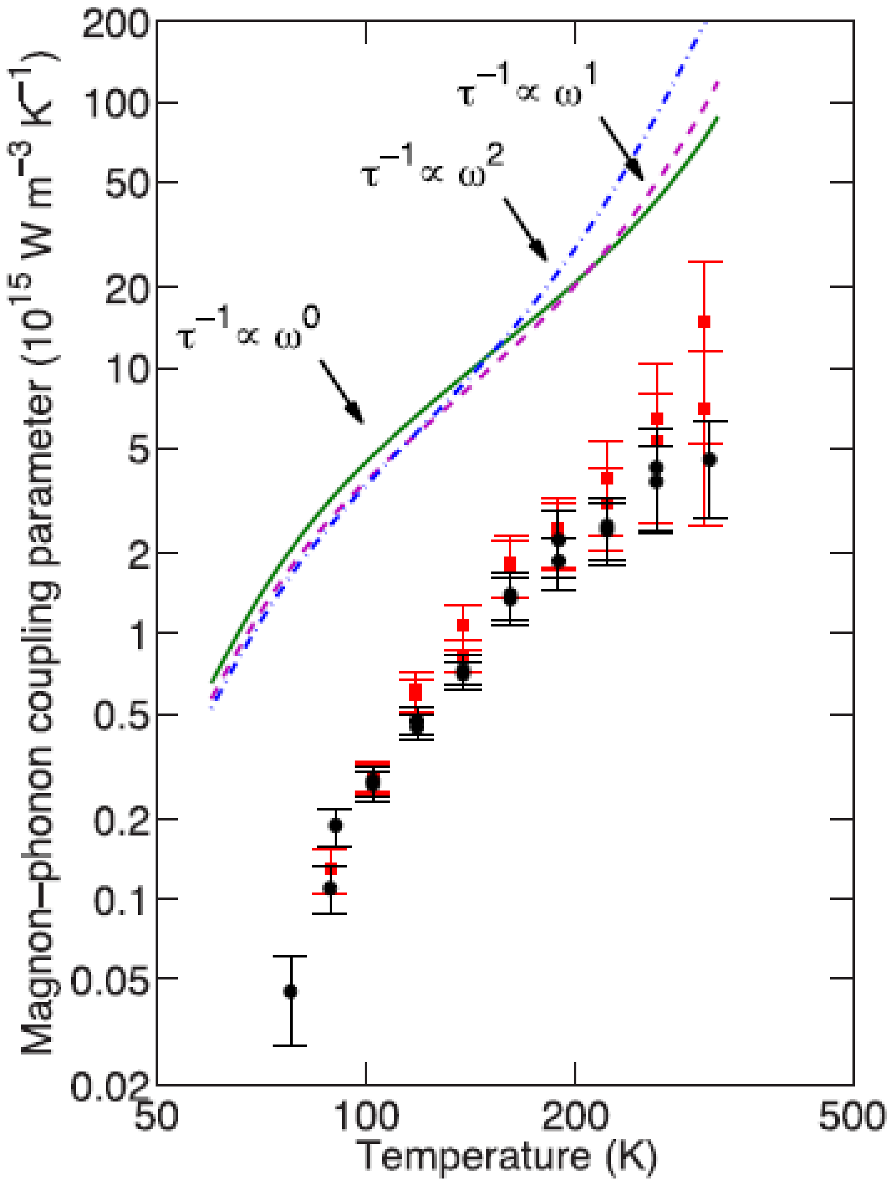
- Model calculations for 10 MHz TDTR experiment. The coupling parameter g is adjusted to get the best fit to the frequency dependent data



Hohensee *et al.*, PRB (2014)

Magnon-phonon coupling in the spin ladder is strongly *T*-dependent

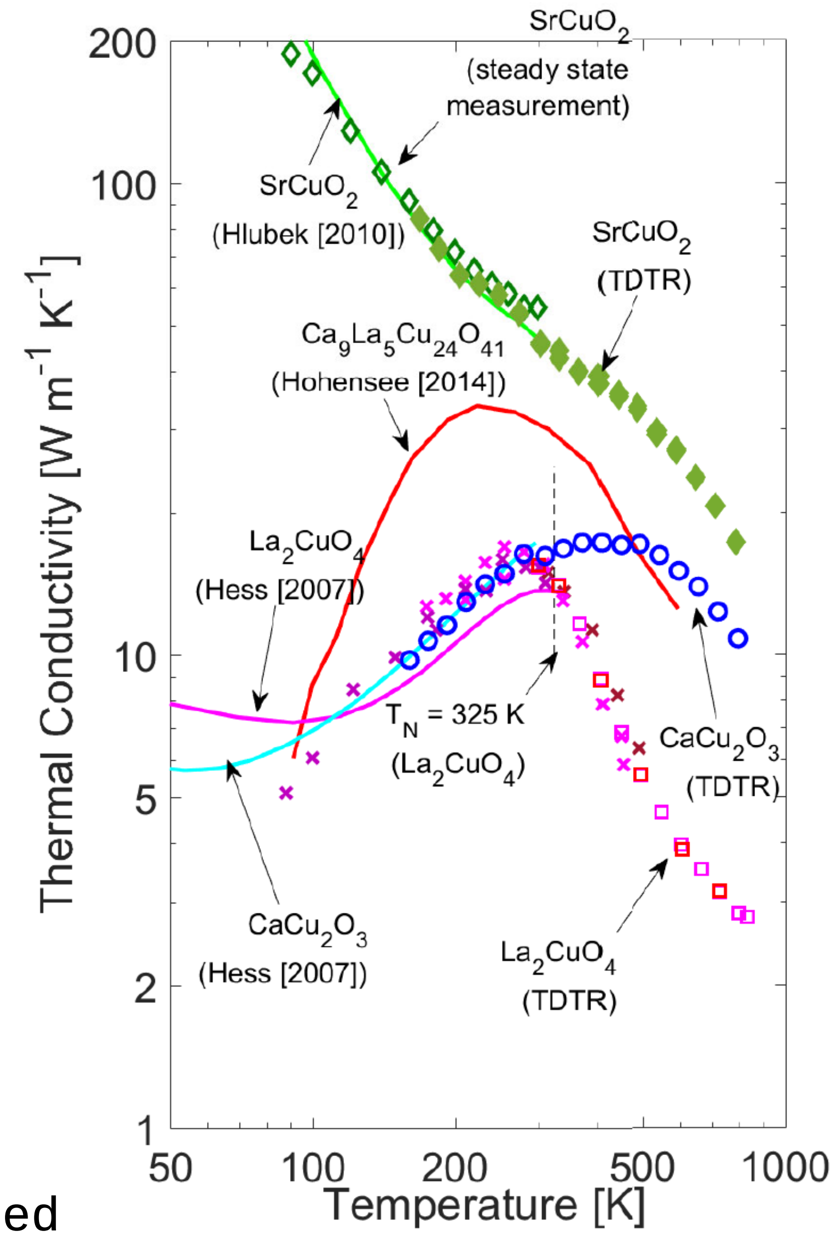
- g_{mp} > 3×10^{15} W m^{-3} K^{-1} near room temperature (10 times smaller than g_{ep} for Au.)
- But is “two temperatures” too crude of a model to capture the physics?



Hohensee *et al*., PRB (2014)

High magnon thermal conductivity is not limited to spin-ladders

- We have not (yet) observed thermal decoupling of phonons and magnons in these other cuprates. Interface thermal conductance is difficult to optimize.



Pek, unpublished

Often, length-scales are more relevant (better connected to the experiment) than time-scales

- Kapitza length is the thickness of the substrate that has the same thermal resistance as the interface

$$L_K = \frac{\Lambda}{G} \approx \frac{\Lambda_p}{G_{pp}} \sim \frac{8 \text{ W/m-K}}{170 \text{ MW/m}^2\text{-K}} \sim 50 \text{ nm}$$

- Healing length L_{mp} for the equilibration of magnons and phonon

$$L_{mp} = \frac{1}{\sqrt{g_{mp}(\Lambda_m^{-1} + \Lambda_p^{-1})}} \approx \sqrt{\frac{\Lambda_m}{g_{mp}}} \sim \sqrt{\frac{0.3 \text{ W/m-K}}{10^{15} \text{ W/m}^3\text{-K}}} \sim 20 \text{ nm}$$

Also consider the effective thermal conductance of the phonon system with thickness of the healing length

$$G_{mp}^{YIG} = \frac{\Lambda_p}{L_{mp}} \approx \sqrt{\frac{\Lambda_p^2 g_{mp}}{\Lambda_m}} \sim 500 \text{ MW m}^{-2}\text{ K}^{-1}$$

- If the heat is entering the magnon system directly from the NM electrons, then the effective conductance is smaller by $\left(\Lambda_m / \Lambda_p\right) \approx 30$
- Can do the same analysis for the electron-phonon system in the metal. For Au, this thermal conductance is large but not infinite

$$G_{ep}^{Au} \approx \sqrt{\Lambda_p g_{ep}} \sim \sqrt{(3 \text{ W/m-K})(3\times 10^{16} \text{ W/m}^3\text{-K})} \sim 300 \text{ MW m}^{-2}\text{ K}^{-1}$$

$$G_{ep}^{Pt} > 1 \text{ GW m}^{-2}\text{ K}^{-1}$$

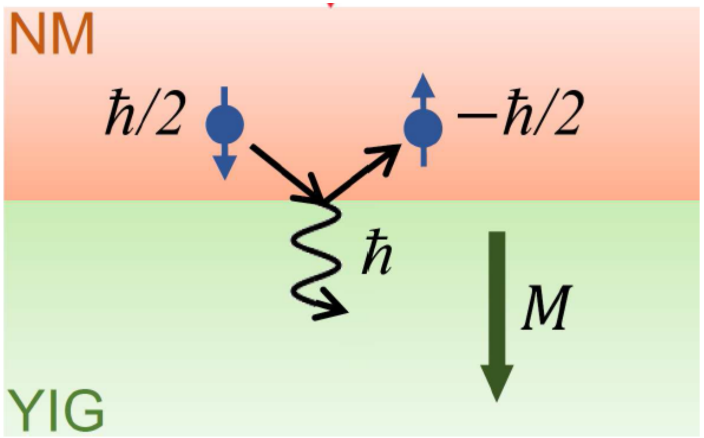
Finally, consider G_{em} , thermal coupling of electrons in NM with magnons in YIG

- Currently, the best way to estimate G_{em} is through the spin transport.
- Might be possible to measure the magnon temperature excursion near the interface directly. (Working on that…)

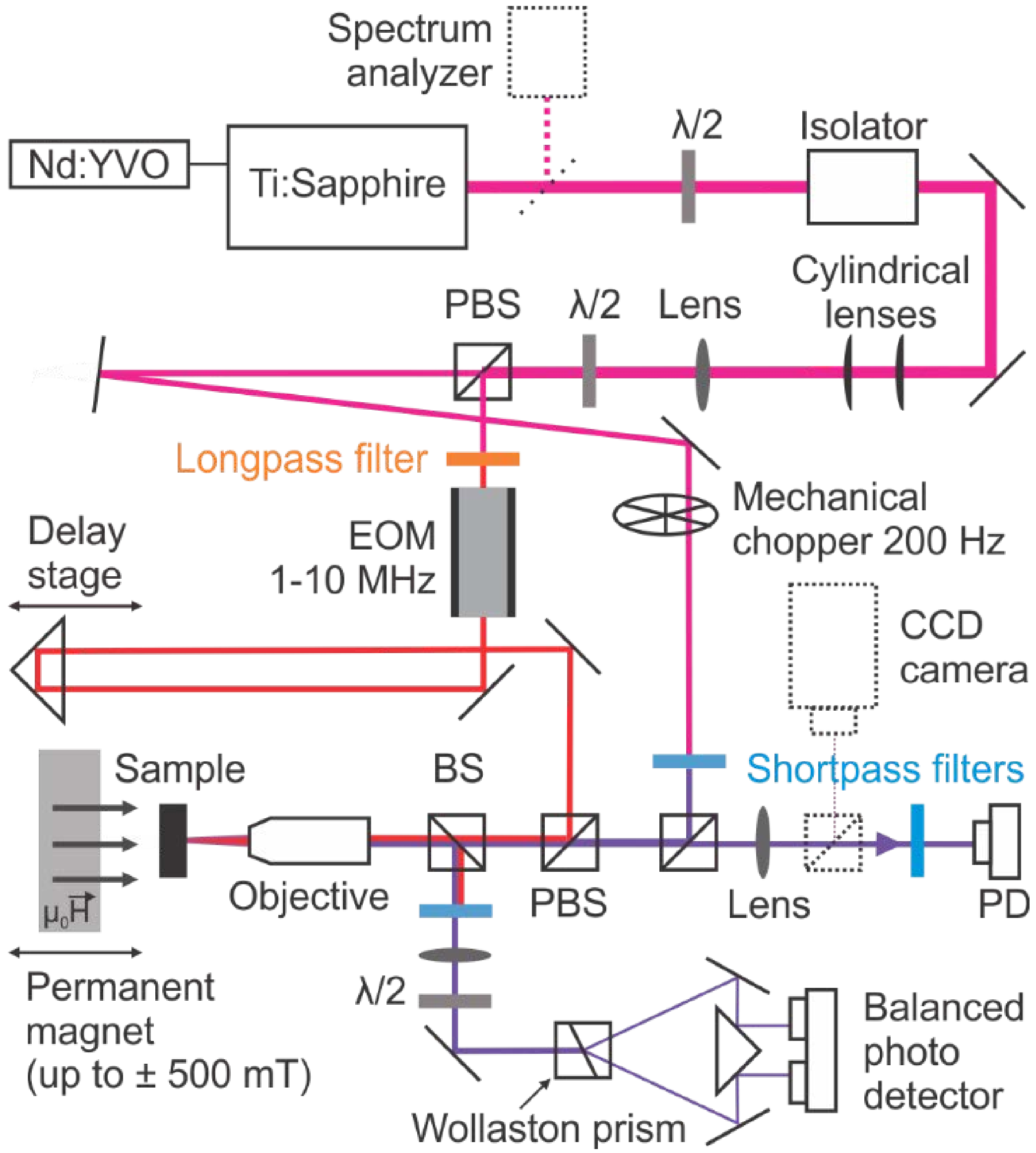
$$j_S = g_{\uparrow\downarrow}\frac{e^2}{h}S_S(T_e - T_m) \qquad S_S = \left(\frac{\gamma h}{\pi M_s V_a}\right)\left(\frac{k_B}{e}\right)$$

$$\alpha \equiv g_{\uparrow\downarrow}\frac{e^2}{h}S_S$$

$$G_{em} \approx \alpha\left(\frac{k_B T}{2e}\right)$$



Detect spin accumulation and magnetization dynamics by time-resolved magneto-optic Kerr effect (TR-MOKE)



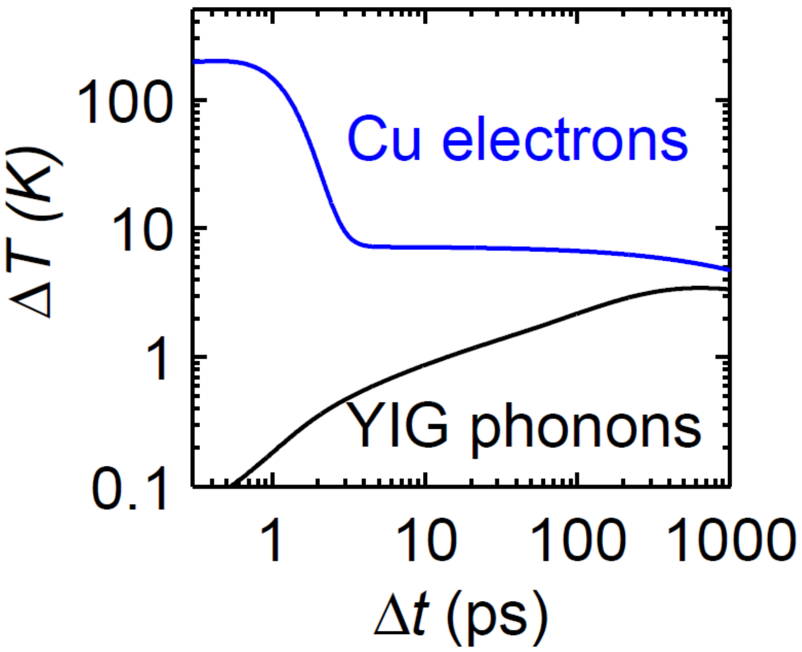
First solve the heat problem

Solve two-temperature model in Au (or Cu) and couple to phonons in YIG through an interface thermal conductance.

For Cu:

$$C_e \frac{\partial T_e}{\partial t} - \Lambda_e \frac{\partial^2 T_e}{\partial z^2} = g_{ep}(T_p - T_e)$$

$$C_p \frac{\partial T_p}{\partial t} - \Lambda_p \frac{\partial^2 T_p}{\partial z^2} = g_{ep}(T_e - T_p)$$

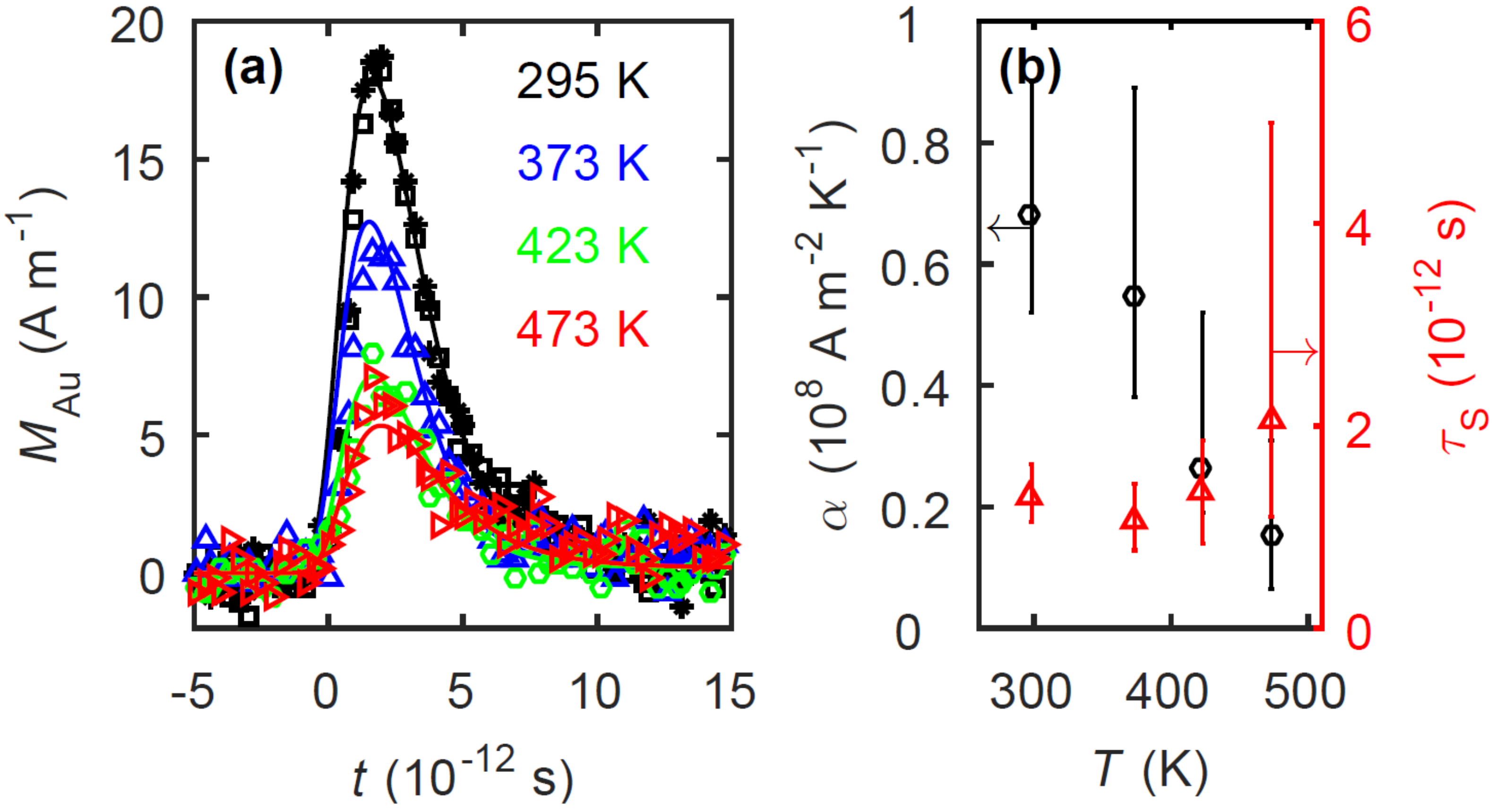


Kimling *et al*., PRL (2017)

Measure spin accumulation in Cu or Au by the polar Kerr effect and convert to magnetization using a previously determined calibration

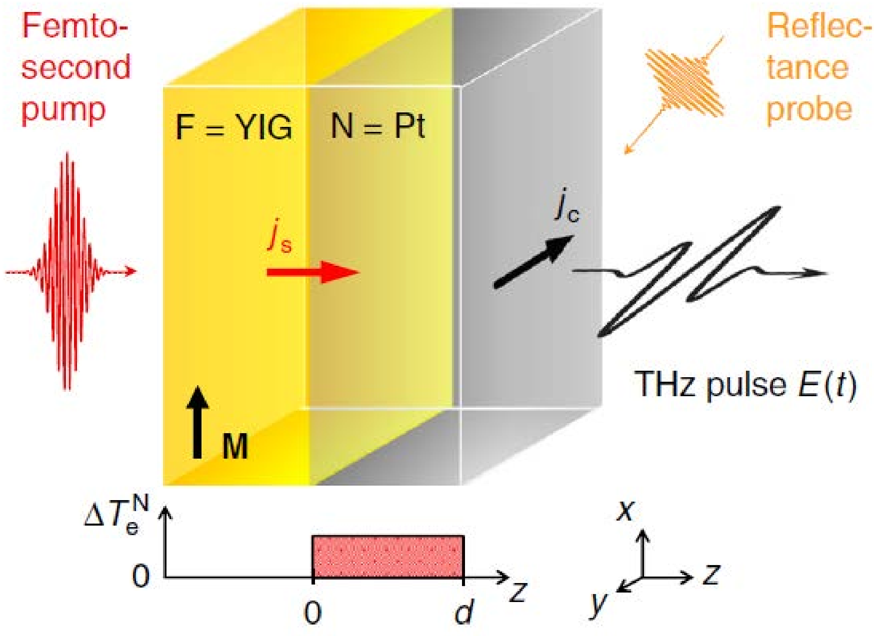
Cu: $\theta_K \approx (10\ \mathrm{nrad\ m\ A^{-1}})M$ Au: $\theta_K \approx (50\ \mathrm{nrad\ m\ A^{-1}})M$

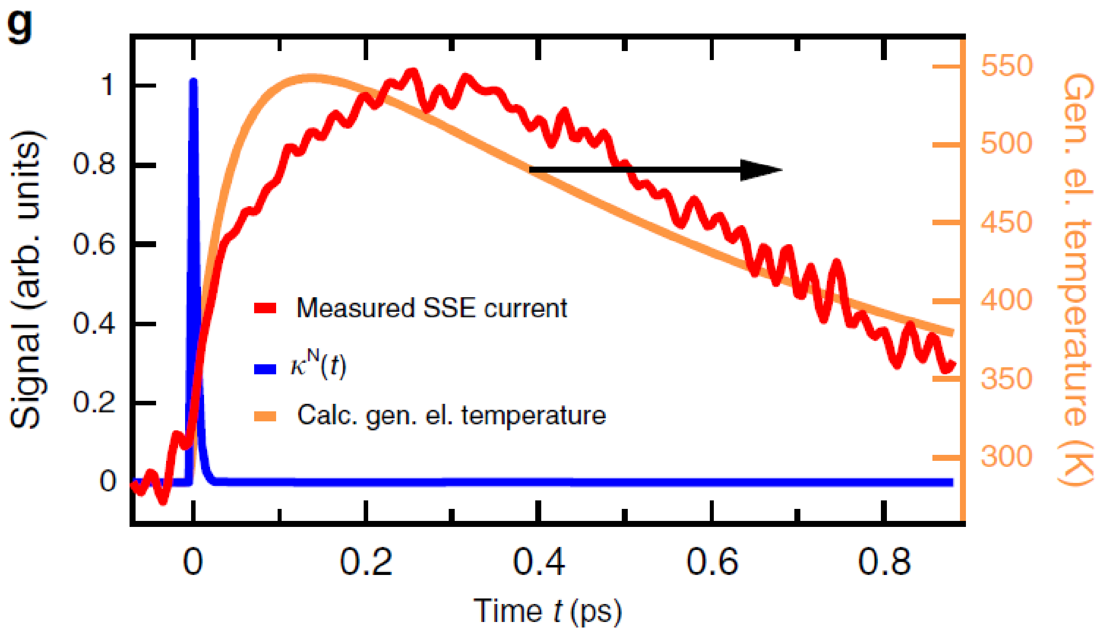
Au(60 nm)/YIG(20 nm)



Kimling *et al.*, PRL (2017)

Seifert (and 20 co-authors) Nat. Comm. (2018) used THz spectroscopy to obtain a factor of 30 better time resolution (order of 30 fs)



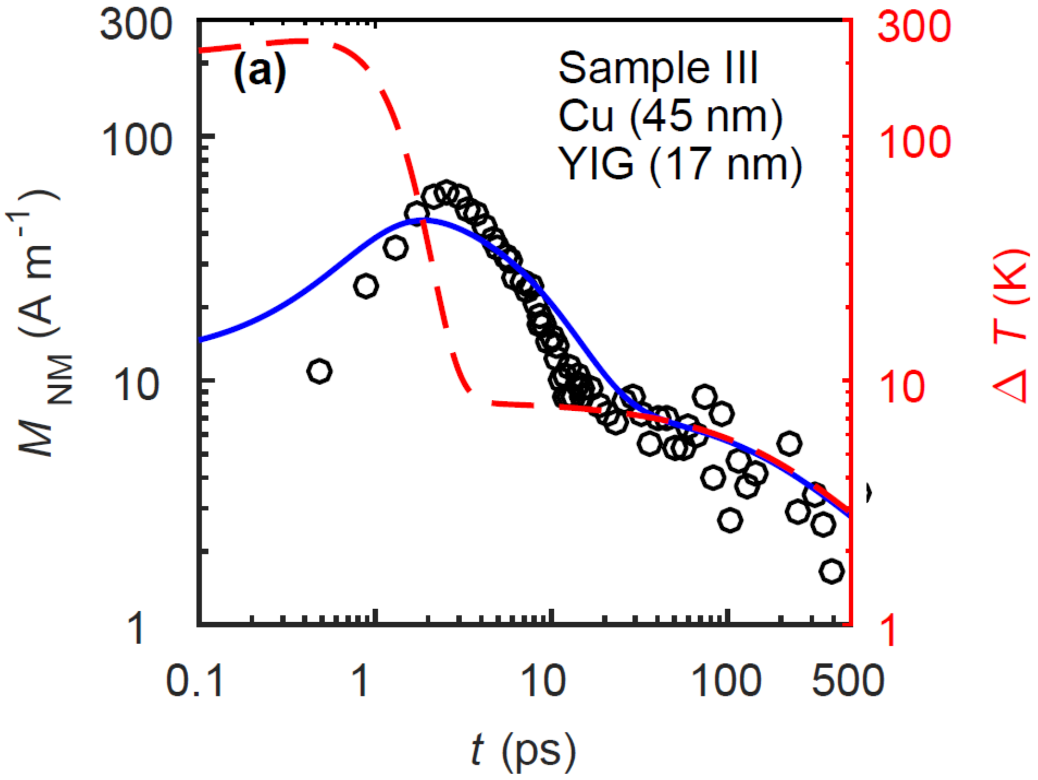


G_{em} is small compared to everything else in the problem. Long time decay of signal is also consistent with signal proportional to interface ΔT

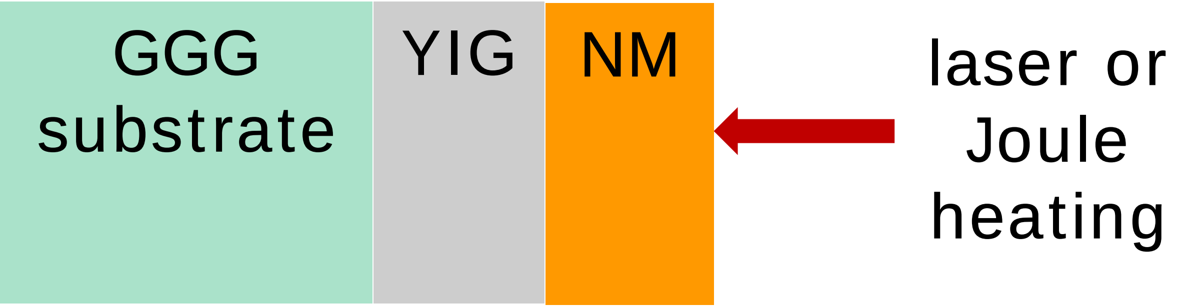
$$G_{em} \approx \left(10^8 \text{ A m}^{-2} \text{ K}^{-1}\right)\left(\frac{k_B T}{2e}\right) \sim 1 \text{ MW m}^{-2} \text{ K}^{-1} \ll \sqrt{\Lambda_m g_{mp}}$$

$$\sqrt{\Lambda_m g_{mp}} \approx 20 \text{ MW m}^{-2} \text{ K}^{-1}$$

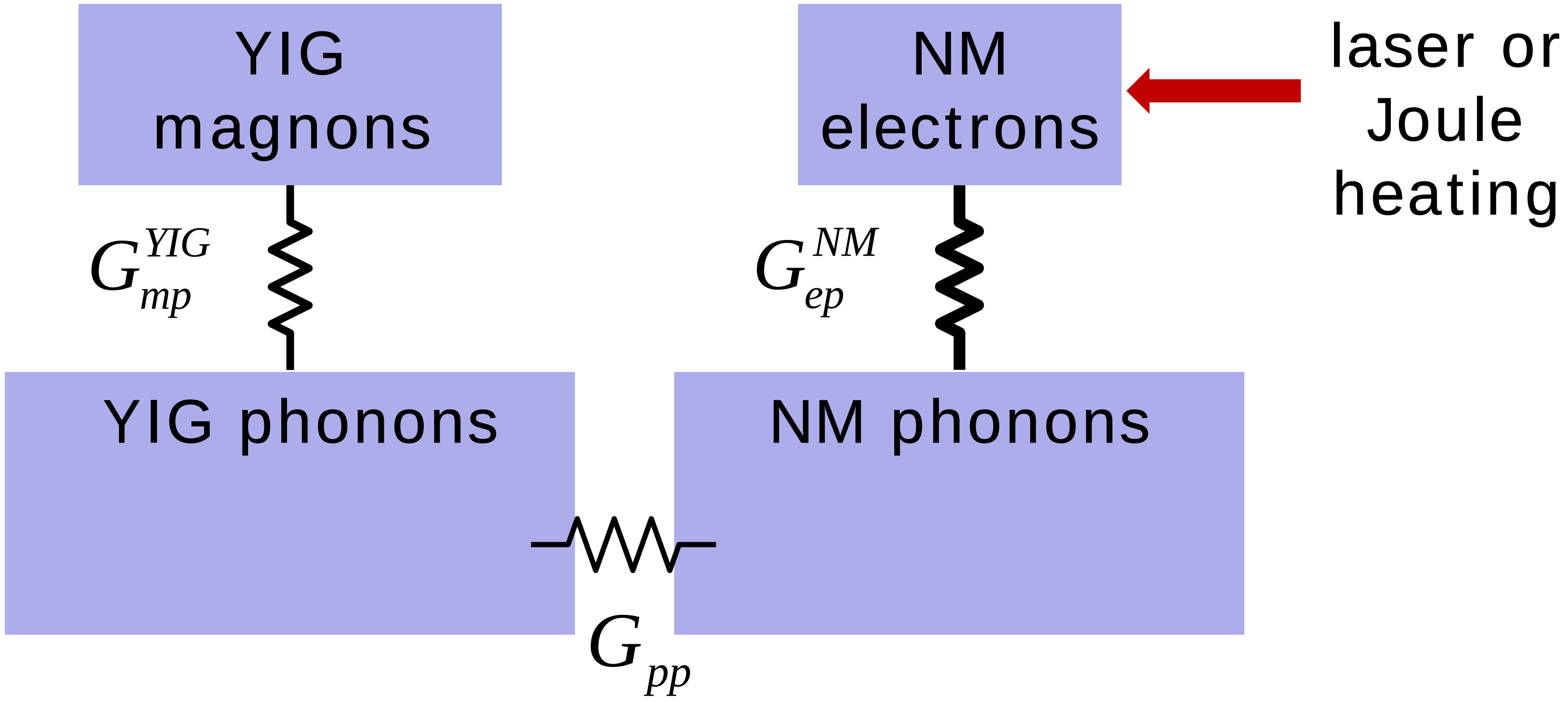
At $t > 3$ ps, $(T_e - T_m) \approx (T_{Cu} - T_{YIG})$



If we only care about ΔT_{em}, and the time-scale is not too short, and G_{em} is negligible, then the thermal circuit simplifies to three conductances in series

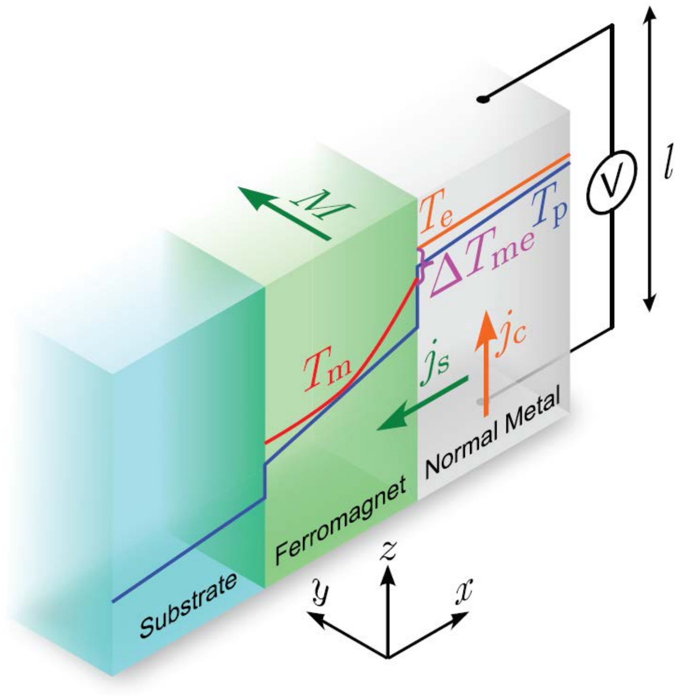


- This model assumes that the YIG thickness is larger than $2L_{mp}$

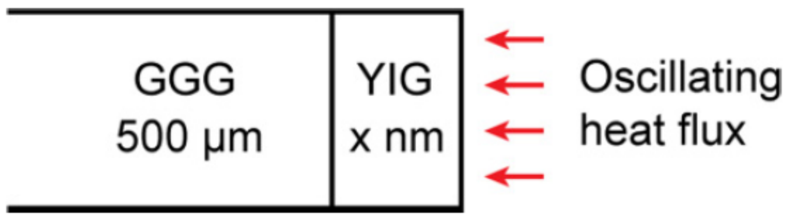


How does this picture compare?

- Schreier *et al.* PRB (2013) seem to assuming G_{em} is large and G_{mp}^{YIG} is small (magnons are hotter than phonons)



- Xu *et al.* PRB (2018) seem to be assuming G_{pp} is infinite (the temperature drop across the NM/YIG interface is assumed to be small)



Open questions for thermal transport at NM/YIG interfaces

- Is a two-temperature model a good description for the magnon-phonon system of YIG?
  - If so, what is the value of g_{mp} (magnon-phonon coupling parameter) at ambient and reduced temperatures?
  - If not, what replaces a TTM?
- What is Λ_m (magnon thermal conductivity) of YIG at T>20 K? What does the suppression of Λ_m in thin films tell us about the material?
- Can we verify the small value of G_{em} (interface thermal conductance between NM electrons and YIG magnons) derived from ps spin transport measurements?