Spin Seebeck effect (theory)
OUTLINE

14:00-14:25: Hiroto Adachi

(10[intro]+5 min. talk + 10 min. discussion)

14:25-14:45: Tamara Nunner

(10 min. talk + 10 min. discussion)

14:45-15:05: Saburo Takahashi

(10 min. talk + 10 min. discussion)

15:05-15:25: Jiang Xiao

(10 min. talk + 10 min. discussion)

15:25-15:30: The last 5 minutes for discussion.

Are *only* phonons relevant to the long-range nature of the spin Seebeck effect?

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In collaboration with

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Special thanks to

K. Uchida, and E. Saitoh

Institute for Materials Research, Tohoku University

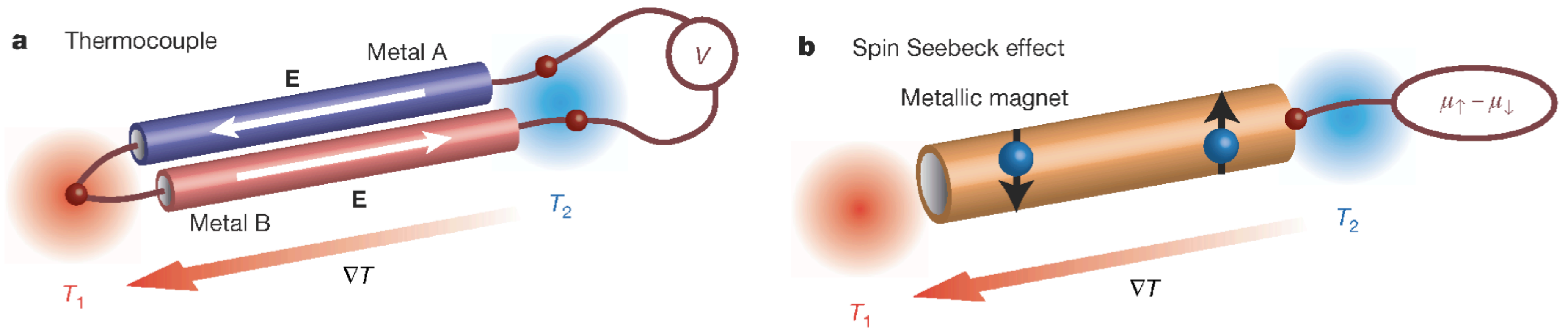
Mar. 11, 2011. in our office …

Spin Seebeck effect (SSE): *Universal* aspect of ferromagnets

Metal (*Ni, Fe, Ni-Fe alloy*; Uchida et al. 2008)
Semiconductor (*GaMnAs*; Jaworski et al. 2010)
Insulator (*Yttrium Iron Garnet*, ***Ferrite***; Uchida et al. 2010)

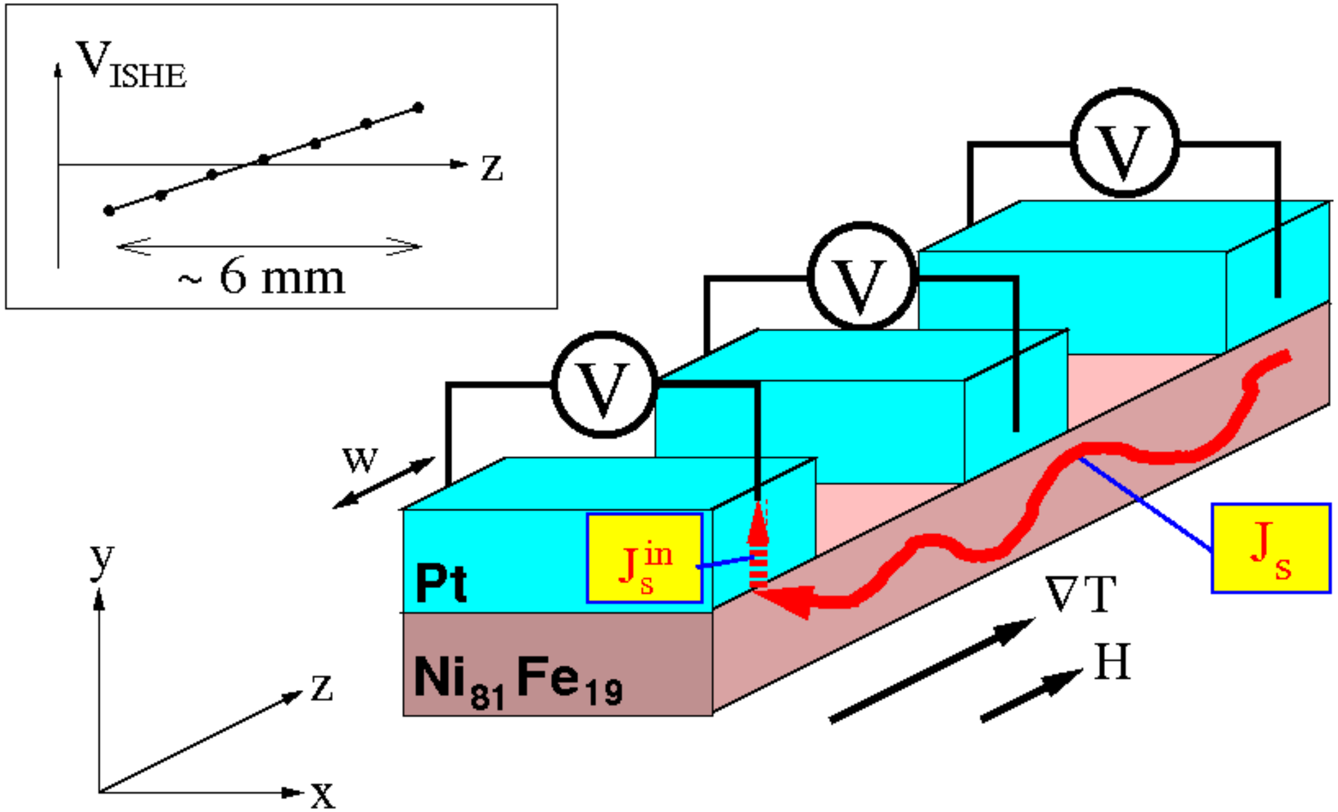
$$\delta V = S\delta T$$

$$\delta V_{spin} = S_{spin}\delta T$$



Uchida et al., Nature 455, 778 (2008)

Review of the original SSE experiment
-- Uchida et al., Nature (2008) --



$$V_{ISHE} = \Theta_H (|e| J_s^{in})(\rho / w) \quad (\boldsymbol{J}_c = \Theta_H \boldsymbol{\sigma} \times \boldsymbol{J}_s)$$

Key Points:

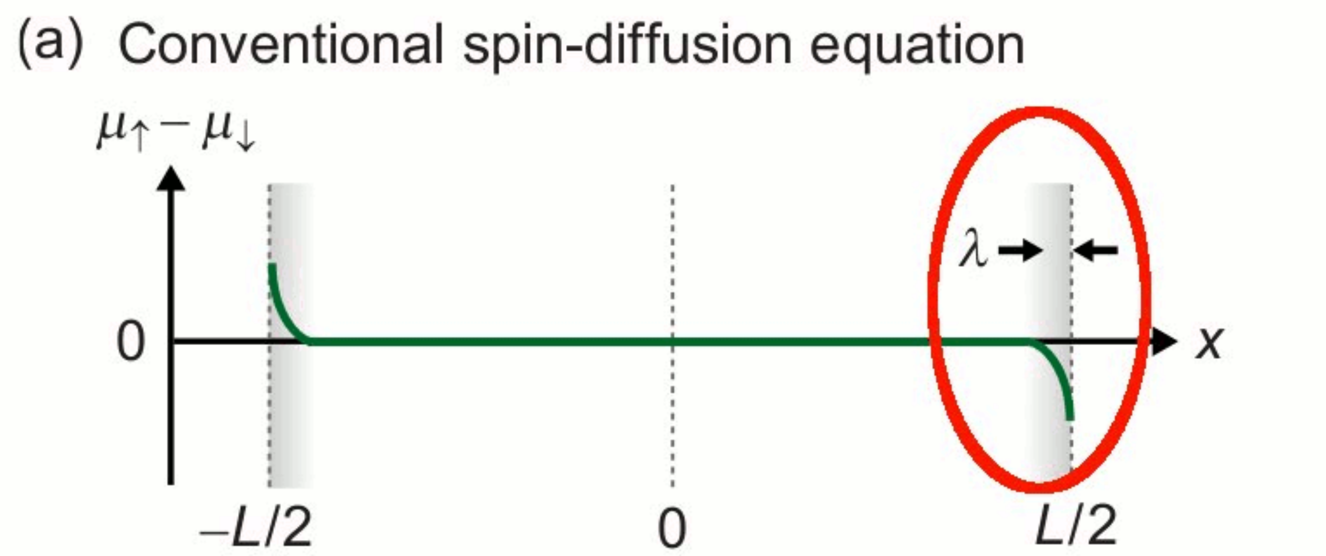
1) $V_{ISHE} \propto J_s^{in}$ (spin current injected into Pt)

2) V_{ISHE} is observed over several millimeters (>> λ_{sf})

Conduction electrons in Py relevant to SSE?
→ seemingly NO!

From experiment … *Spin Seebeck Insulator* (Uchida et al., 2010).

From theory ………. Conduction electrons' short λ_{sf} fails to explain
(Uchida, Hatami) the length scale seen in the experiment.

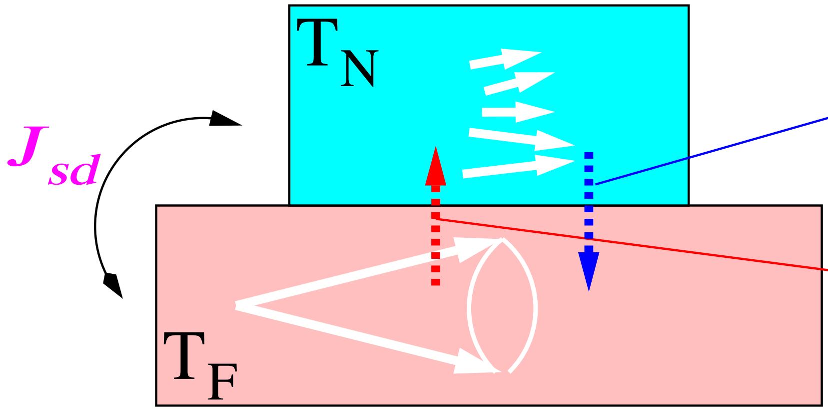


Uchida et al., J. App. Phys. 105, 07C908 (2009)

See however the counter argument by Nunner.

Localized-spin based scenario for SSE

(Spin injection from magnetic insulators: Takahashi)



$$J_s^{\rm back} = -A \cdot T_N \quad \text{(=noise in N)}$$

$$J_s^{\rm pump} = A \cdot T_F \quad \text{(=noise in F)}$$

$$\therefore J_s^{in} = A(T_F - T_N)$$

$$\left(A \propto J_{sd}^{\ 2} \int d\omega \frac{1}{\omega} \mathrm{Im}\,\chi_N(\omega)\, \mathrm{Im}\,X_F(\omega) \right)$$

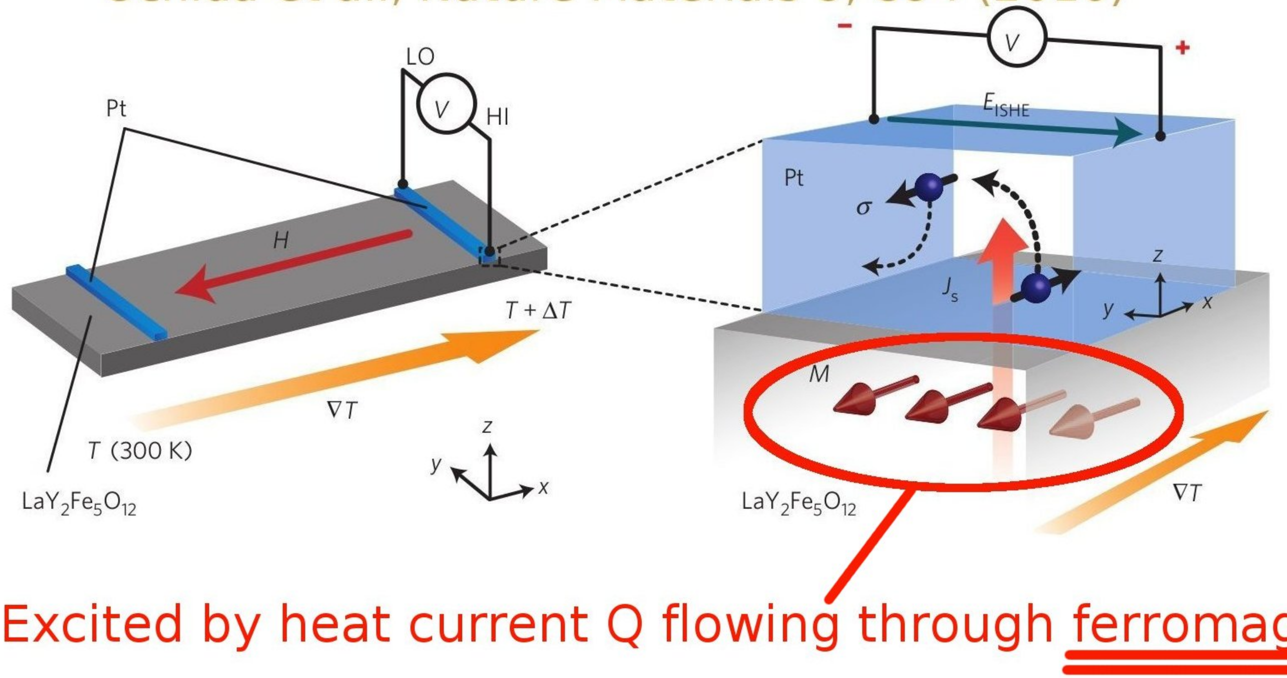
At local thermal equilibrium,
***pumping flow* (noise in F) and *back flow* (noise in N) cancel.**

When F deviates from local thermal equilibrium
→ Finite spin injection!

Essence of localized-spin based scenario

Localized spin in the ***Ferromagnet*** is excited by ***heat current Q*** flowing through the ***Ferromag***.

Uchida et al., Nature Materials 9, 894 (2010)



Excited by heat current Q flowing through ferromag.

Note: $Q=Q_{mag}+Q_{ph}$

Accordingly, there are TWO relevant processes!

(i) Magnon driven SSE (Xiao, PRB 2010)

Localized spin is excited by magnon heat current Q_{mag}.

PHYSICAL REVIEW B **81**, 214418 (2010)

Theory of magnon-driven spin Seebeck effect

Jiang Xiao (萧江),[1,2] Gerrit E. W. Bauer,[2] Ken-chi Uchida,[3,4]
Eiji Saitoh,[3,4,5] and Sadamichi Maekawa[3,6]

In principle, the theory holds for both ferromagnetic insulators and metals. However, as shown above, the theory fails for ferromagnetic metal Py, which underestimates the length scale λ and overestimates the magnitude ξ. This might have two reasons: (i) the lack of reliable information about relaxation times $\tau_{\mathrm{mp,m}}$ for Py and (ii) the complication due to the existence of conduction electrons in ferromagnetic metals.

TABLE I. Parameters for YIG and Py.

	YIG	Py	Unit
λ (th)	0.85–8.5	0.3	mm
λ (expt.)		4.0[j]	mm

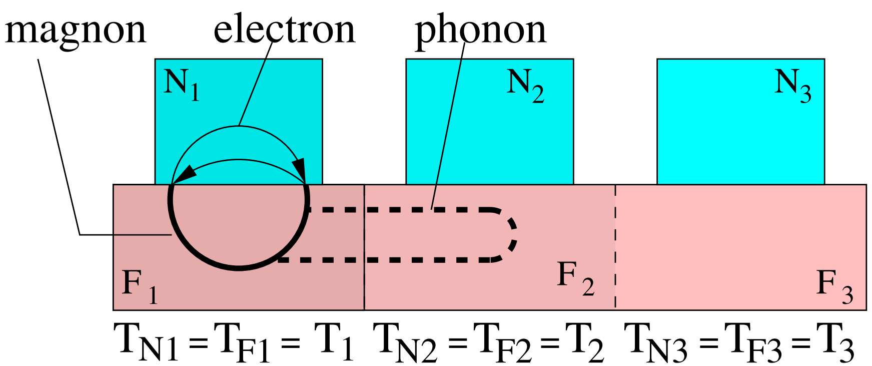
Concerning the length scale, this explains YIG, but fails to explain Py??

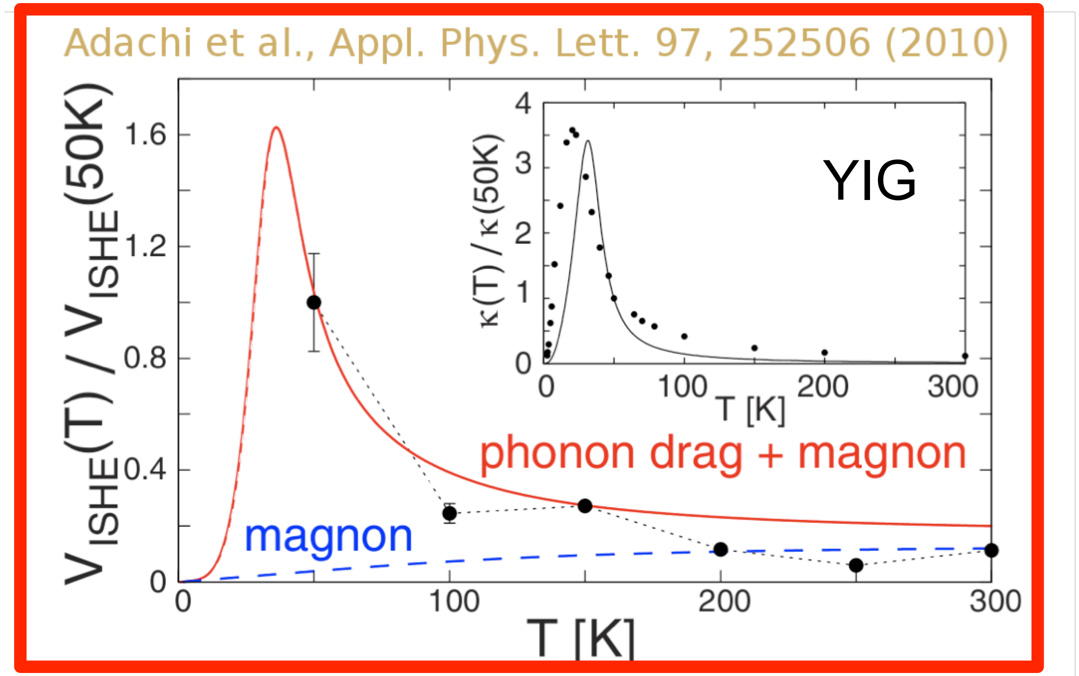
Other possibility of the localized-spin based scenario for SSE?

→YES! (phonon-drag SSE)

(ii) Phonon-drag SSE (Adachi, APL 2010)

Localized spin in ferromagnet is excited by ***phonon*** heat current





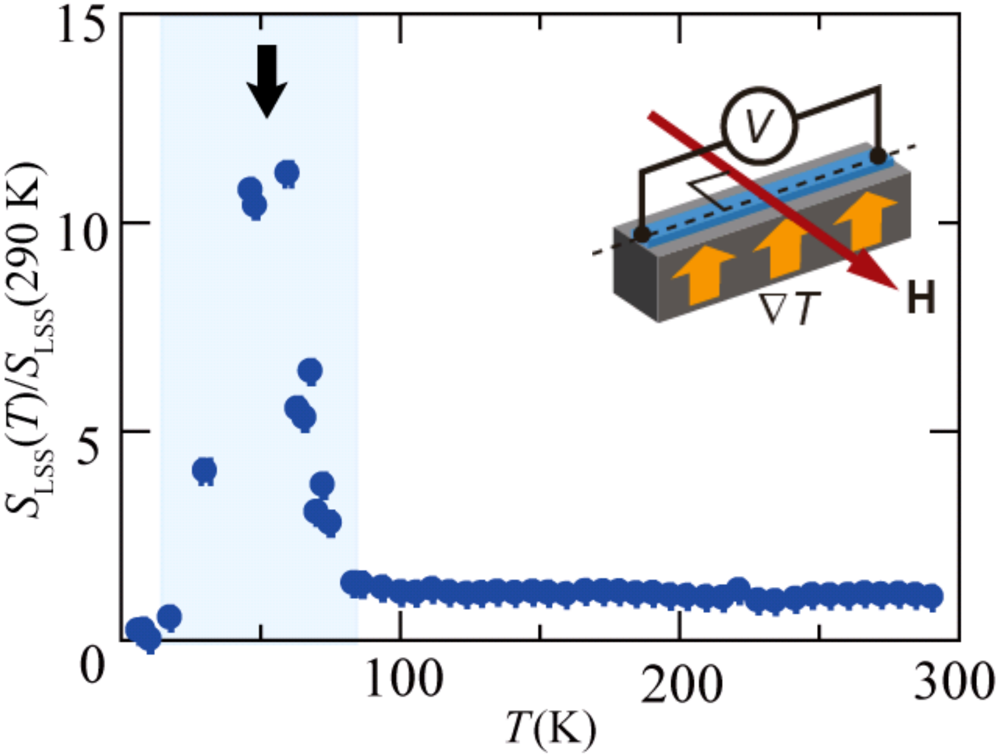
$$J_s^{ph-drag} \propto \tau_{ph} \left(T_{ph} - T_{elec} \right)$$

At low T (< 100K), phonon lifetime (tau_{ph}) gets longer due to the rapid suppression of the umklapp scatt.

→ *Phonon-drag gives low-T enhancement of SSE!*

Very recent data

YIG (Ota et al., submitted)

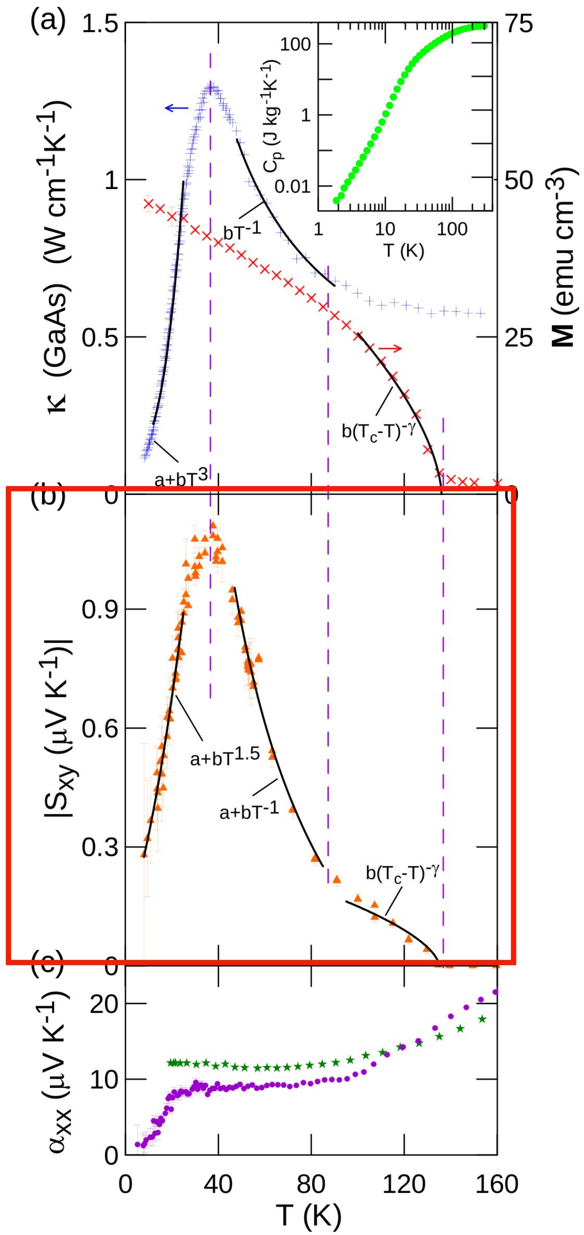


T. Ota *et al.*, (submitted).

Pronounced peak consistent with the theory prediction!

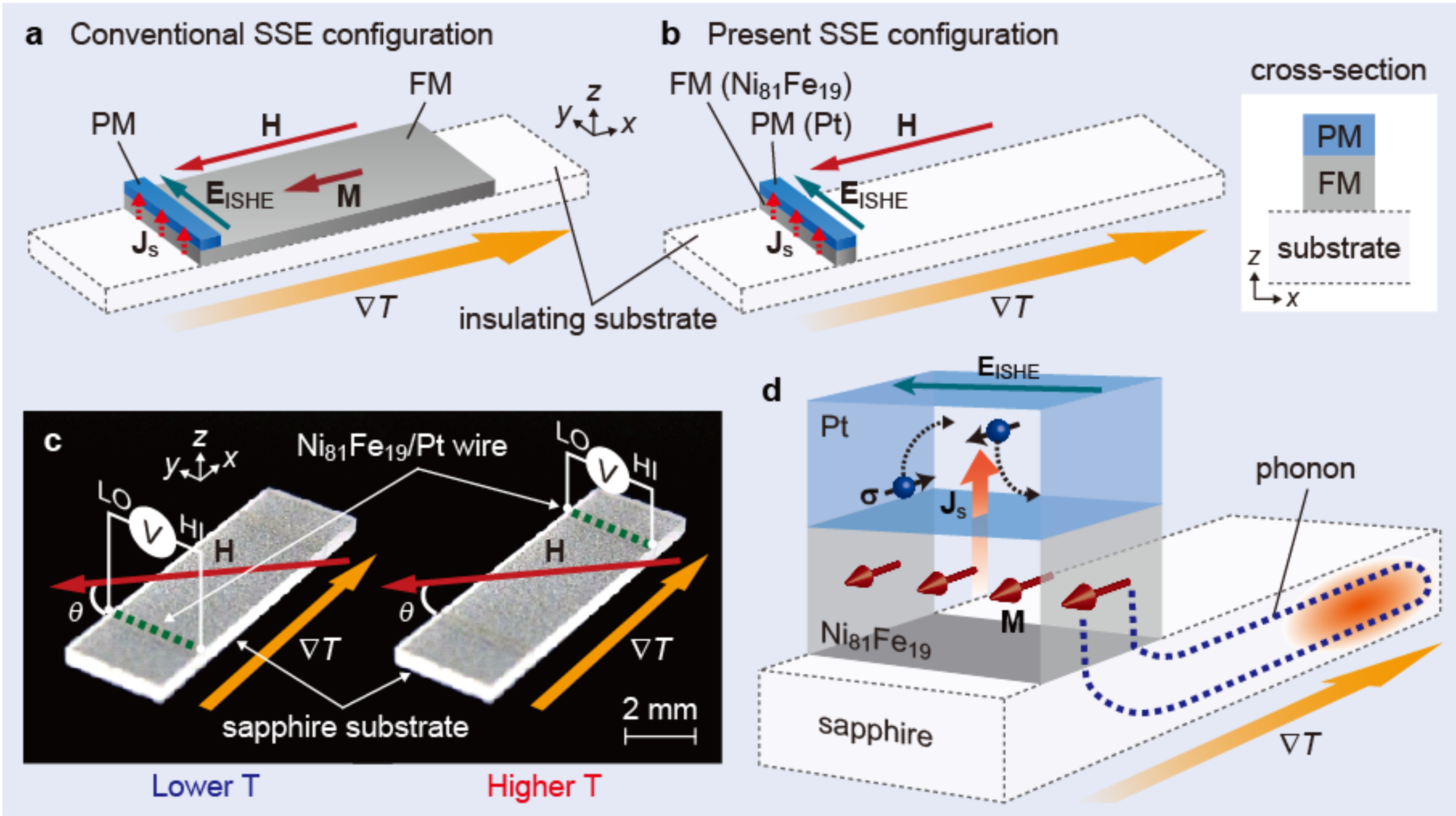
GaMnAs (Jaworski et al).

Jaworski et al., arXiv:1102.1024



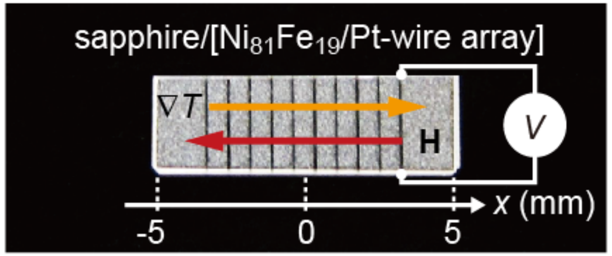
Direct evidence of the phonon-drag SSE

-- Uchida and Saitoh, unpublished (2011) --

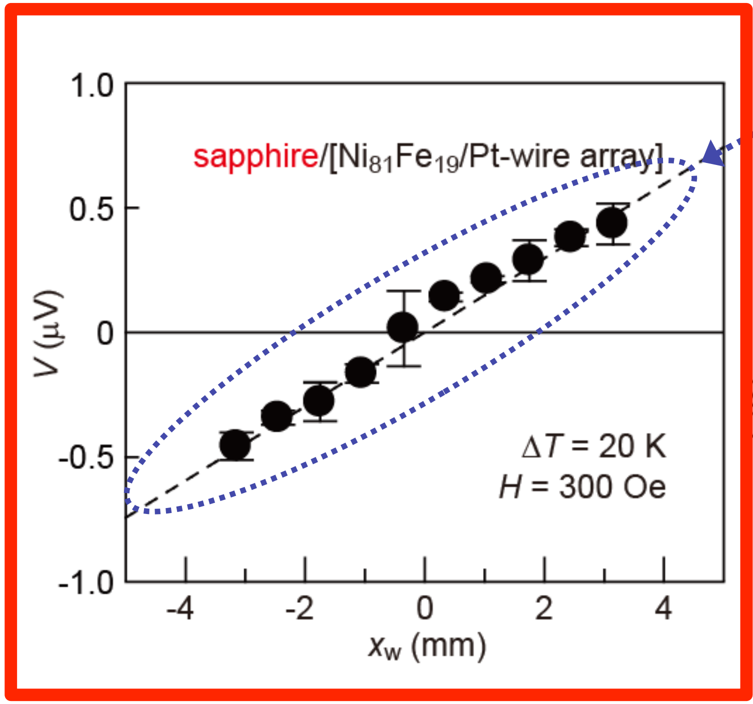


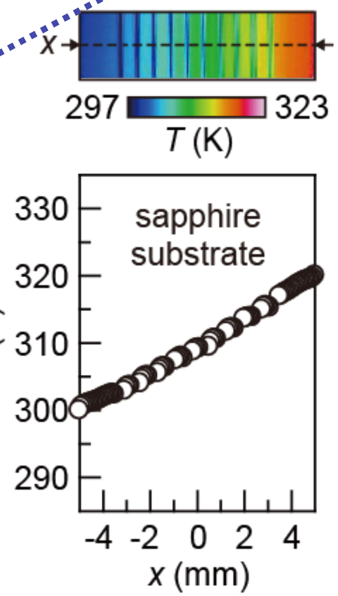
A sample consisting of a **$Ni_{81}Fe_{19}$/Pt bilayer wire** placed **on top of a single-crystal sapphire substrate**, where only ***phonons*** can pass through the substrate.

Length scale of the phonon-drag SSE



V varies almost linearly along the ∇T direction
+
$V = 0$ at $x_w = 0$





The SSE appears even in the ***isolated*** $Ni_{81}Fe_{19}$/Pt wire on the insulating substrate.

Phonon can explain the long-range nature of the SSE in ferromagnetic METALS.

SUMMARY

- ***Phonon drag*** can explain the long-range nature of the SSE.

QUESTION

- Can ***conduction electron/magnon*** explain the SSE in ***ferromagnetic metals***?