NEWSPIN2 at Texas (December 15-17, 2011)

Phonon-Drag on Spin Seebeck Effect

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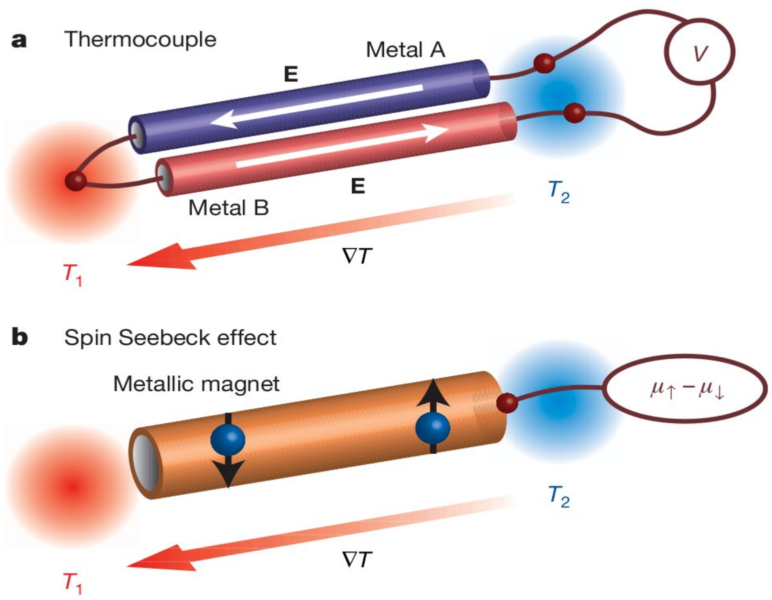
Seebeck effect vs. Spin Seebeck effect:



Electric voltage

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

$$\uparrow$$

(Inverse Spin Hall effect)

$$\uparrow$$

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

Spin accumulation
(Spin voltage)

c.f., G. Bauer's talk

Seebeck effect :
Entropy flow vs. charge current,

Spin Seebeck effect :
Entropy flow vs. spin current.

⟶ *Inverse spin Hall effect*

*c.f., S. Maekawa et a.:"**Physics of Transition metal oxides"** (Springer, 2004)*

Content:

Spin wave Spin Current:

"Linear response theory"

* *Spin Seebeck effect:*

*in YIG (K. Uchida et al.: **Nature Materials ((2010))***

*in (Ga,Mn)As (C.M.Jaworski et al.: **Nature Materials ((2010))**.*

* *in Fe-Ni/Pt hybrid wires (K.Uchida et al.:Nature Materials ((2011)).*

Theory:

H,Adachi, J.Ohe, S, Takahashi, J. Ieda (JAEA).

Experiment:

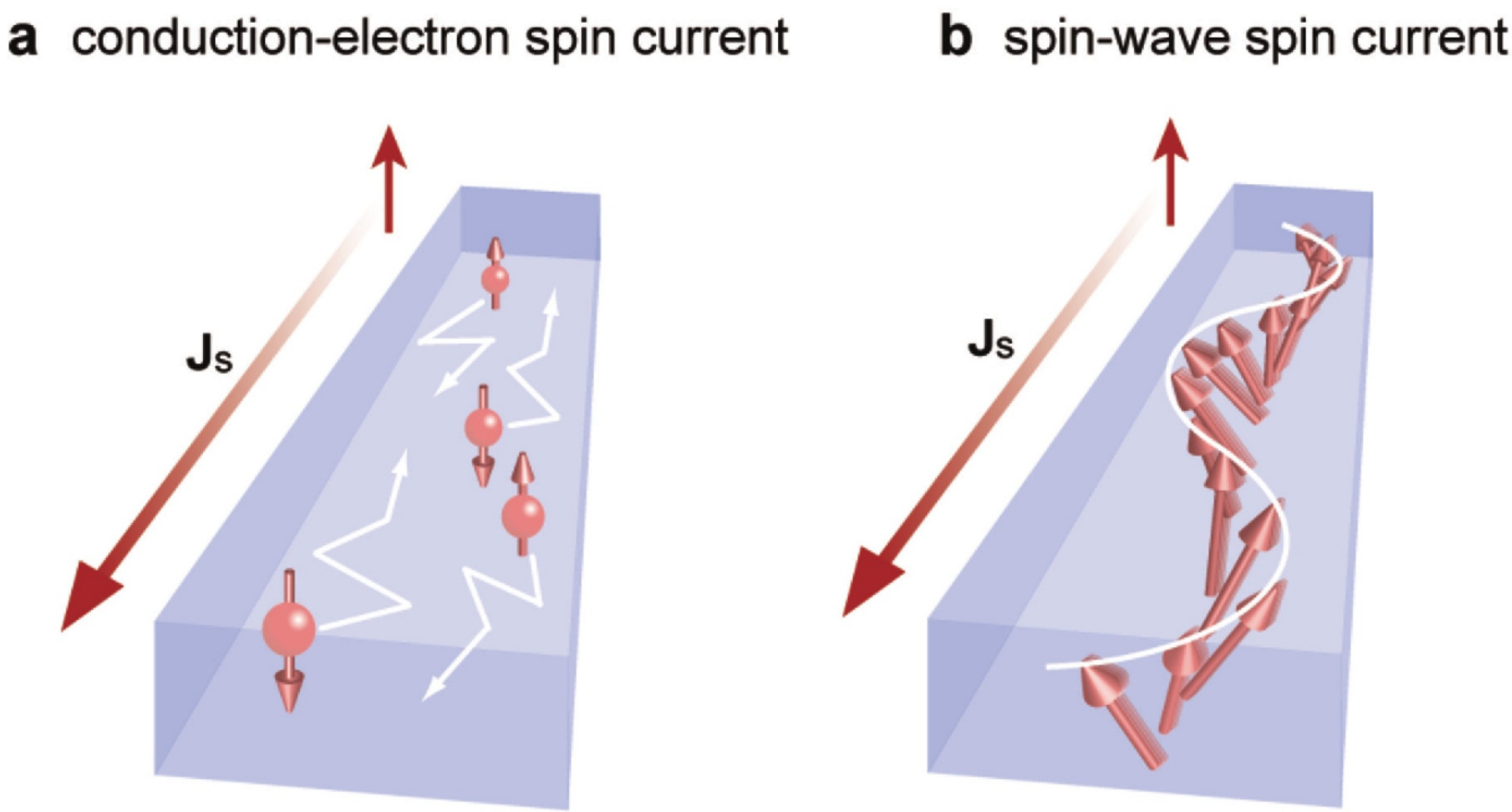
E. Saitoh, K. Uchida, Y. Kajiwara, K. Ando (Tohoku University), J. Heremans and his colleagues (Ohio State University).

Acknowledgements:

G. Bauer (Tohoku/Delft), J. Xiao (Fudan), B. Hillebrants (Kaiserlautern),

R. Ibarra (Zaragoza), S. Rezende (Recife)

Dissipative spin currents :



$$\begin{cases} j = j_{\uparrow} + j_{\downarrow} \\ j_{\text{spin}} = j_{\uparrow} - j_{\downarrow} \end{cases}$$

Kajiwara et al., Nature 464, 262 (2010)

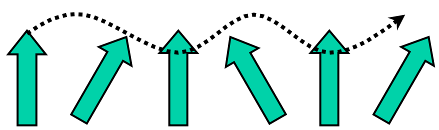
Insulating magnets are good spin current conductors!!

Spin Seebeck effect is a general phenomenon in ferromagnets:

Ferromagnetic metals Py. Fe, Co Ni etc.
Ferromagnetic inslators YIG, Ferrites.
Ferromagnetic semiconductors (Ga,Mn)As: Michigan State U. + UCSB

"Spin waves are common in ferromagnets"

Propagating spin wave



$$j_s = \sum_{\mathbf{q}} n_{\mathbf{q}} \mathbf{v}_{\mathbf{q}} = \sum_{q} n_q v_q + n_{-q} v_{-q} \qquad \mathbf{v}_{\mathbf{q}} = 2D\mathbf{q}$$

n : Magnon number

$n_q = n_{-q}$: Standing wave

$n_q \neq n_{-q}$: Propagating wave (spin-wave spin current)

Spin current is a non-equilibrium quantity!

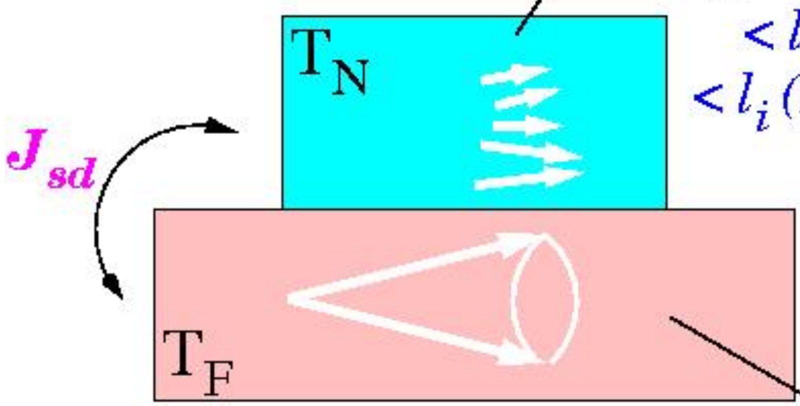
Model for spin injection by thermal magnons

Nonmagnetic metal (N)

$$\frac{d}{dt}\mathrm{s} = \boldsymbol{J}_{sd}\,\mathrm{m}\times\mathrm{s} + (D_N\nabla^2 - \Gamma)(\mathrm{s} - s_0\,\mathrm{m}) + \boldsymbol{l}$$

$$\langle l_i(r)\rangle = 0$$

$$\langle l_i(r,t)\, l_j(r',t')\rangle = 2k_B T(r)\,\chi_N\,\Gamma\,\delta_{ij}\,\delta(r-r')\,\delta(t-t')$$



Ferromagnet (F)

$$\frac{d}{dt}\mathrm{m} = -\boldsymbol{J}_{sd}\,\mathrm{s}\times\mathrm{m} + \gamma(H_{eff} + \boldsymbol{h})\times\mathrm{m} + \alpha\,\mathrm{m}\times\frac{d}{dt}\mathrm{m}$$

$$\langle h_i(r)\rangle = 0$$

$$\langle h_i(r,t)\, h_j(r',t')\rangle = \frac{2k_B T(r)\,\alpha}{\gamma M_s}\,\delta_{ij}\,\delta(r-r')\,\delta(t-t')$$

(c.f., J. Xiao and G. Bauer)

Linear response of LOCAL spin injection by heat

Bloch eq.: $\partial_t \boldsymbol{s} = J_{sd}\boldsymbol{m}\times\boldsymbol{s} + (D_N\nabla^2 - \Gamma)(\boldsymbol{s} - s_0\boldsymbol{m}) + \boldsymbol{l}$ $\quad (s_0 = \chi_N S_0 J_{sd})$

LLG eq.: $\partial_t \boldsymbol{m} = J_{sd}\boldsymbol{s}\times\boldsymbol{m} + \gamma(\boldsymbol{H}_{eff} + \boldsymbol{h})\times\boldsymbol{m} + \alpha\boldsymbol{m}\times\partial_t\boldsymbol{m}$

Injected spin current: $J_s^{in} \equiv \langle \partial_t s^z \rangle = J_{sd}\,\mathrm{Im}\int d\omega \langle s^+(\omega) m^-(-\omega) \rangle$

$$s^+(\omega) = \Gamma s_0 X_F^*(-\omega)\chi_N^*(-\omega)\gamma h^+(\omega) + \chi_N^*(-\omega) l^+(\omega)$$
$$m^-(\omega) = X_F(\omega)\gamma h^-(\omega) + J_{sd} X_F(\omega)\chi_N(\omega) l^-(\omega)$$
$$(a^\pm \equiv a^x \pm i a^y)$$

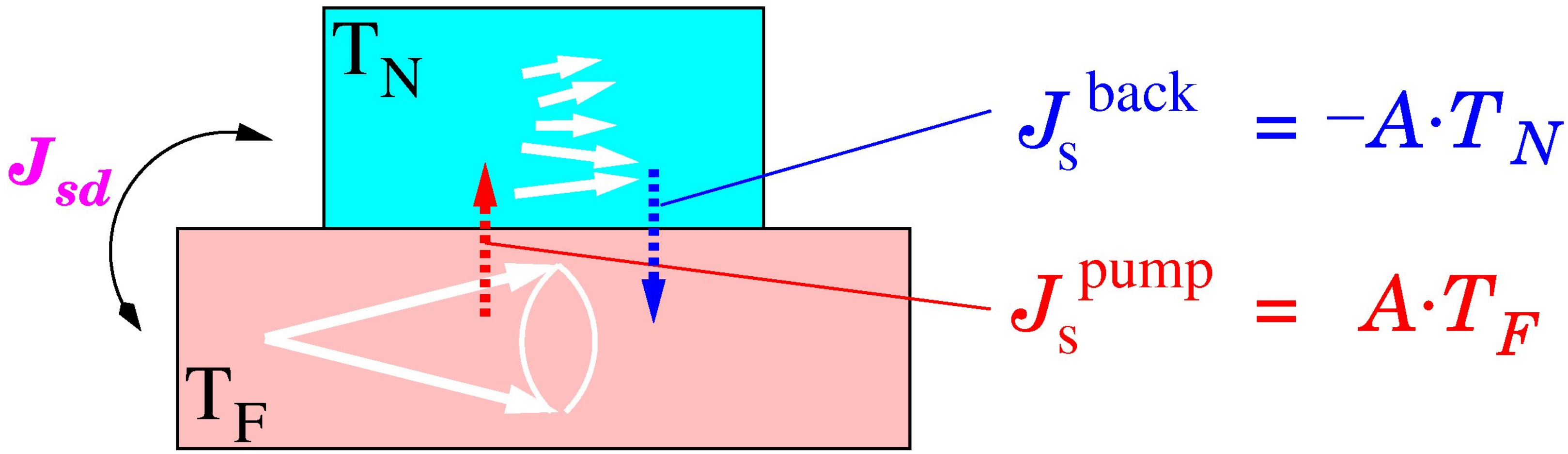
$$J_s^{in} = J_{sd}\int d\omega \frac{1}{\omega}\mathrm{Im}\,\chi_N(\omega)\,\mathrm{Im}\,X_F(\omega)\left[\Gamma s_0 \langle \gamma h^+(\omega)\gamma h^-(-\omega)\rangle - \alpha J_{sd}\langle l^+(\omega) l^-(-\omega)\rangle\right]$$

J_s^{pump} $\quad$ J_s^{back}

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

SSE is a competition between
pumping flow **(noise in F) and** ***back flow*** **(noise in N)**

local spin injection by magnons



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

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

$$J_s^{in} \equiv < \partial_t s^z > = J_{sd}\,\mathrm{Im}\int d\omega < s^+(\omega) m^-(-\omega) >$$

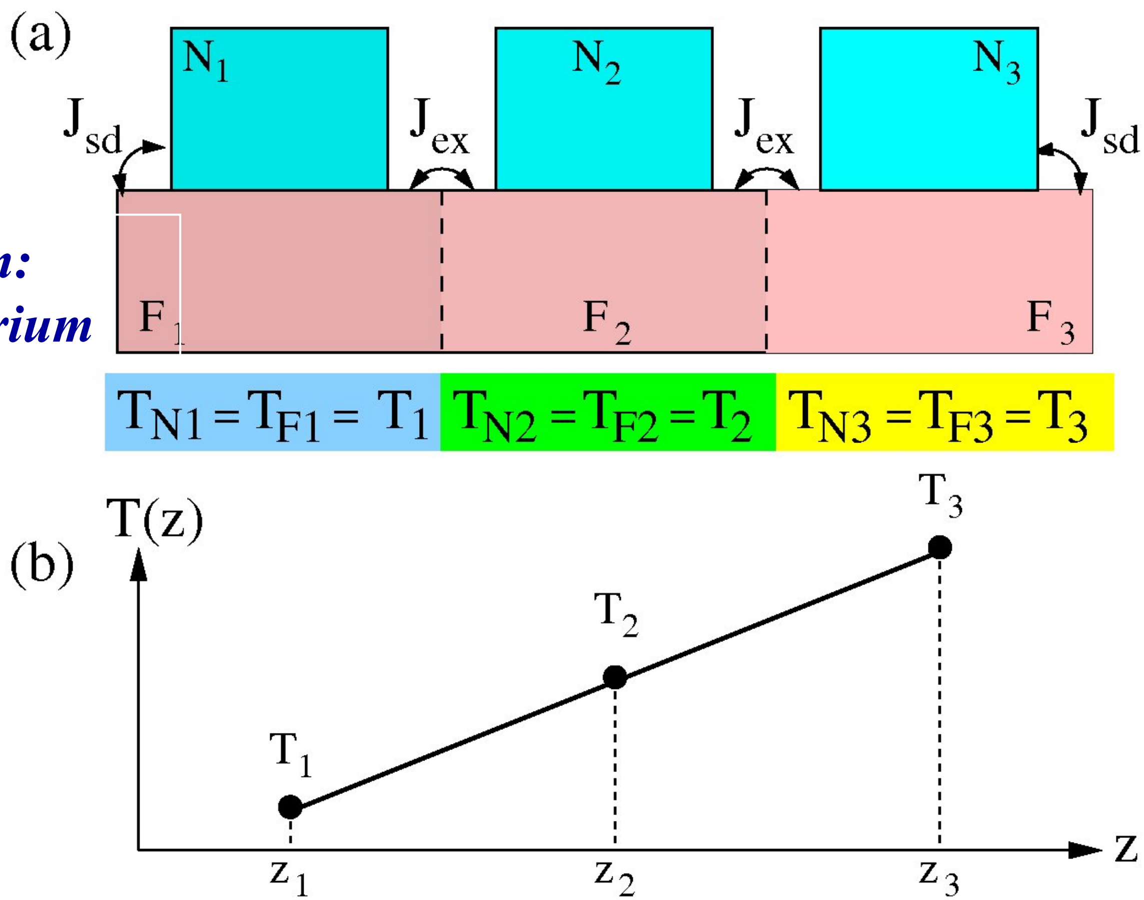
$\longrightarrow$ *(Field theoretical calculation of Green's function)*

No temp-diff. between Pt and YIG in the experiment

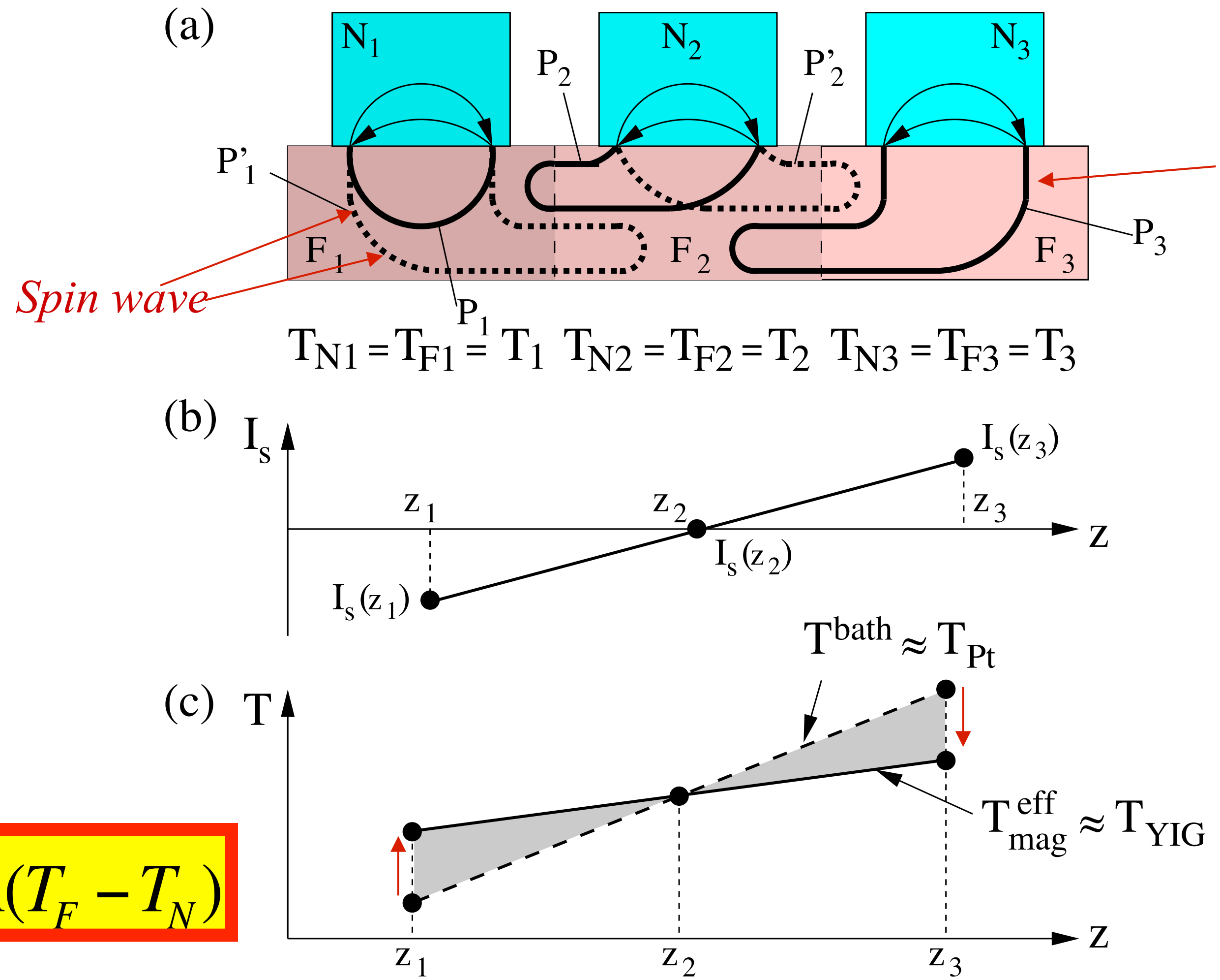
➔need to consider the effect of **temp-gradient** in YIG

Consider the following model

Static condition:
Local equiliburium



Interpretation by magnon effective temp.



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

Magnon at higher (lower) temp. feels lower (higher) temp.

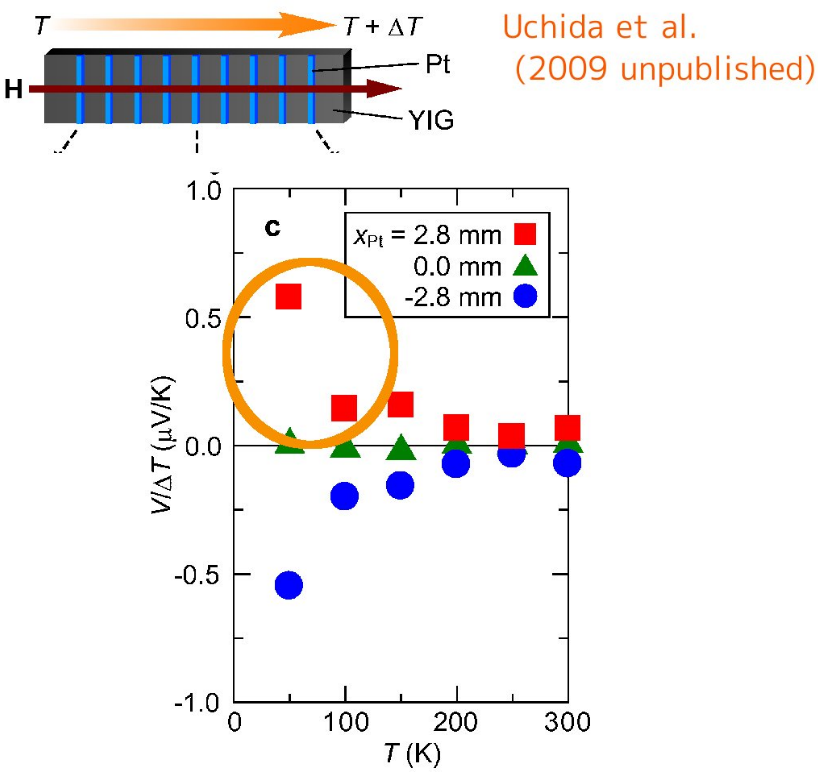
→ Spin wave dynamics for spin Seebeck effect.

T-dependence of $J_s^{ph\text{-}drag}$:

$$J_s^{ph-drag} \propto \tau_{ph} \Delta T$$

$J_s^{ph\text{-}drag}$ shows low-temp. enhancement due to the rapid suppression of umklapp scatt.

(←Similar phenomenon known in thermoelectrics)



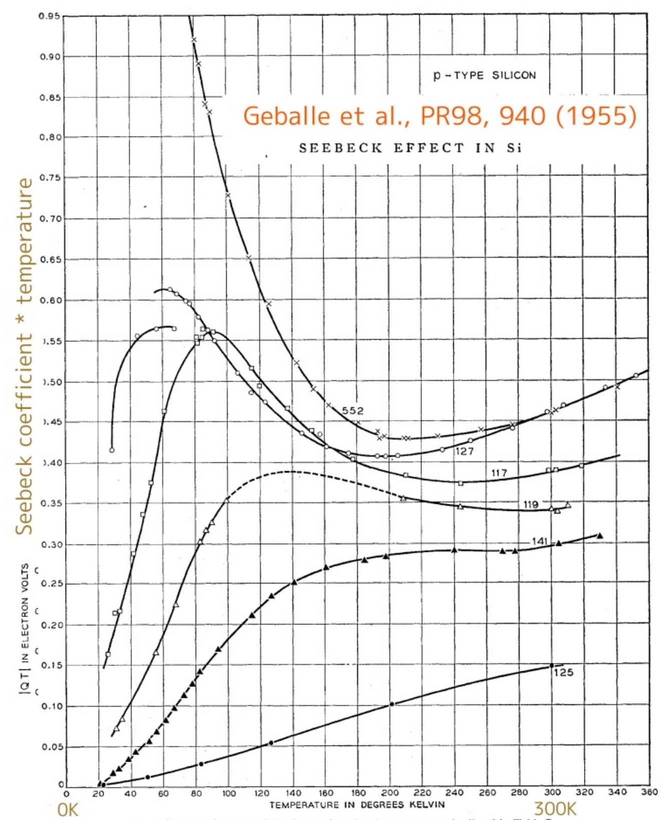


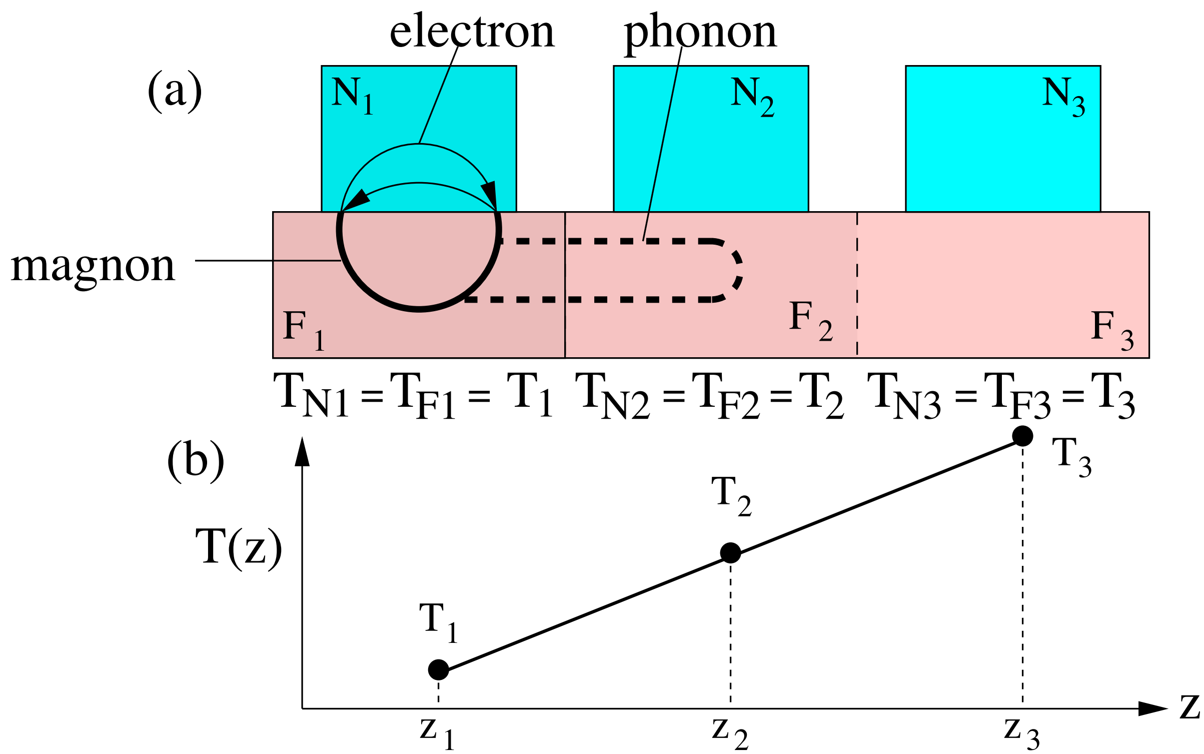
FIG. 2. Measured values of the QT product for six p-type samples listed in Table I.

Phonon: additional ingredient!

Phonon-drag contribution to SSE

Phonon drag process;

Magnons dragged by nonequilibrium phonons → spin injection



$$J_s^{ph-drag} \propto \tau_{ph} \Delta T$$

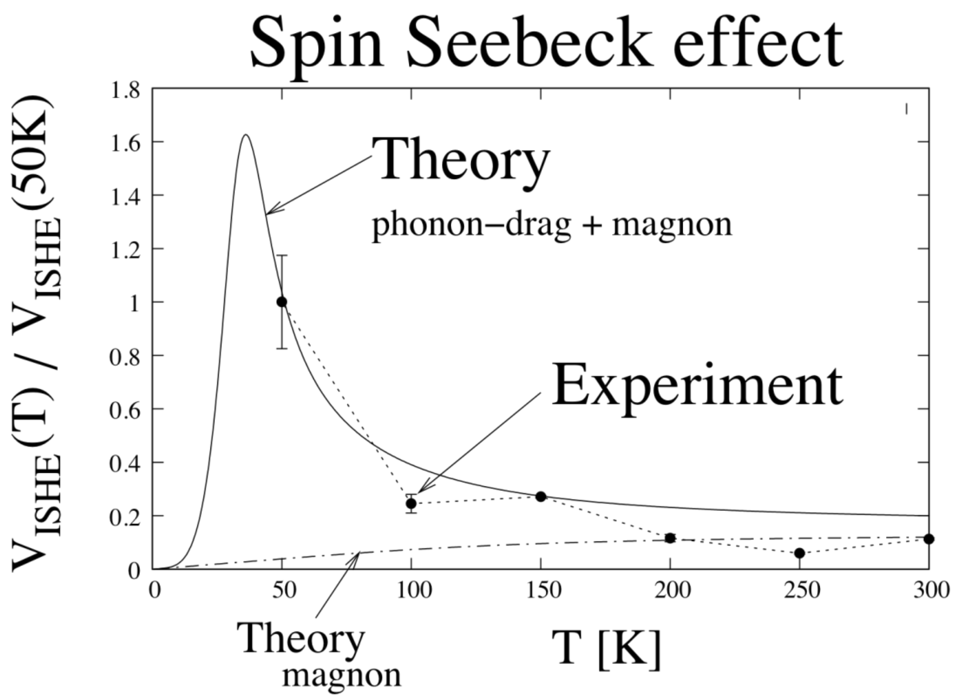
Phonon drag gives low-T enhancement of SSE due to the rapid suppression of umklapp scatt.

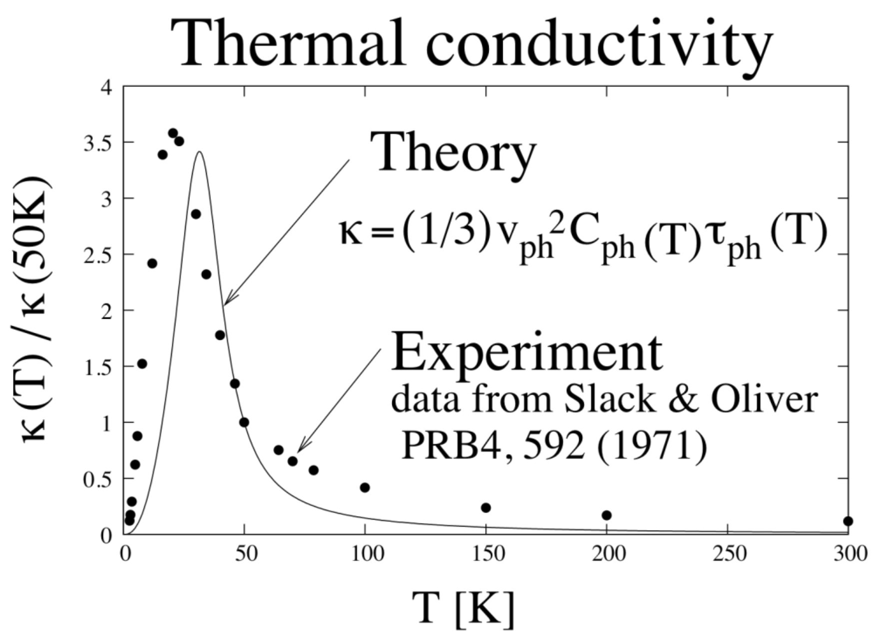
Fitting of the data by our theory

$$J_s^{ph-drag}(T) = const \cdot B_1(T) B_2(T) \tau_{ph}(T)$$

$$\tau_{ph}(T) = \tau^{(0)}{}_{ph} \left(\frac{1}{1 + (1/a)\exp[-b(T_D/T)]} \right) \left(\frac{1}{1 + (1/c)(T/T_D)} \right)$$

$$B_1(T) = (T/T_D)^5 \int_0^{T_D/T} \frac{du u^6}{sh^2(u/2)} \qquad B_2(T) = (T/T_M)^{9/2} \int_0^{T_M/T} \frac{dv v^{7/2}}{th(v/2)}$$

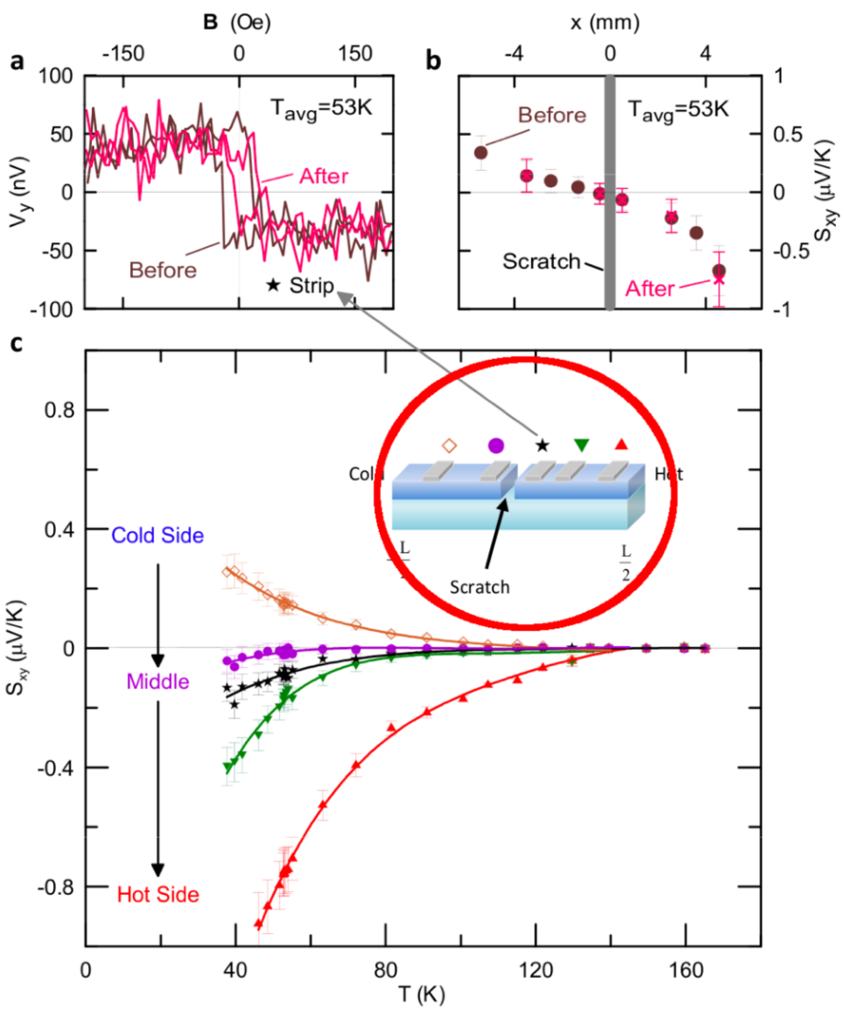




Spin Seebeck eff. without global spin current

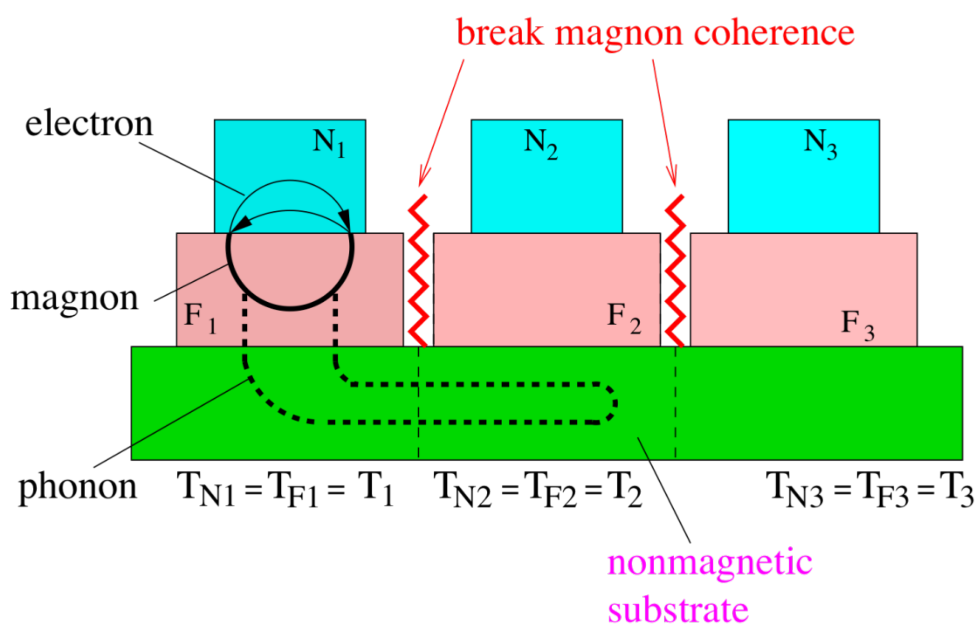
Observation of the Spin-Seebeck Effect in a Ferromagnetic Semiconductor

C. M. Jaworski[1], J. Yang[2], S. Mack[3], D. D. Awschalom[3], J. P. Heremans[1,4*], R. C. Myers[2,4*]

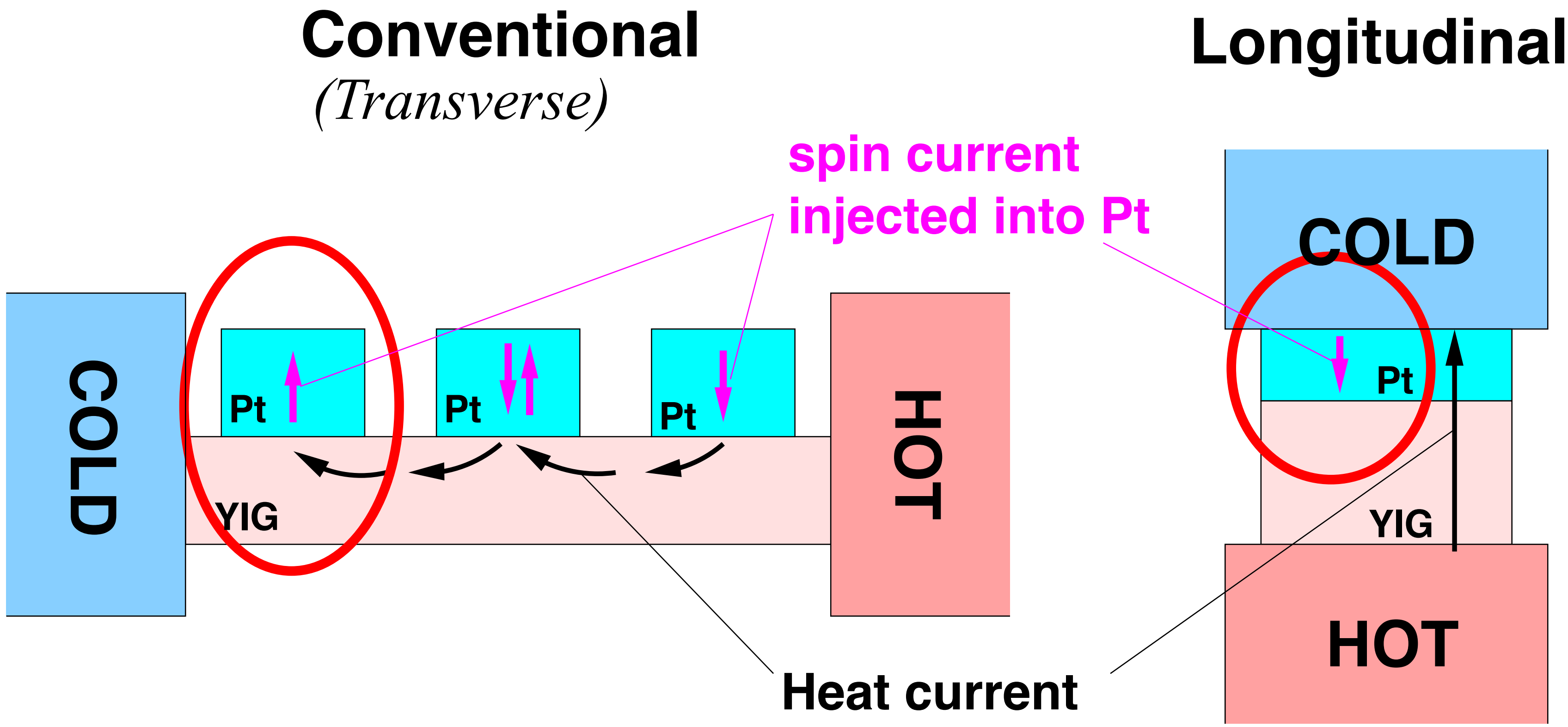


Our interpretation

Phonon drag: Effective at low-T.
GaMnAs: low Curie temp



Longitudinal Spin Seebeck Effect:
(Conventional vs. Longitudinal)

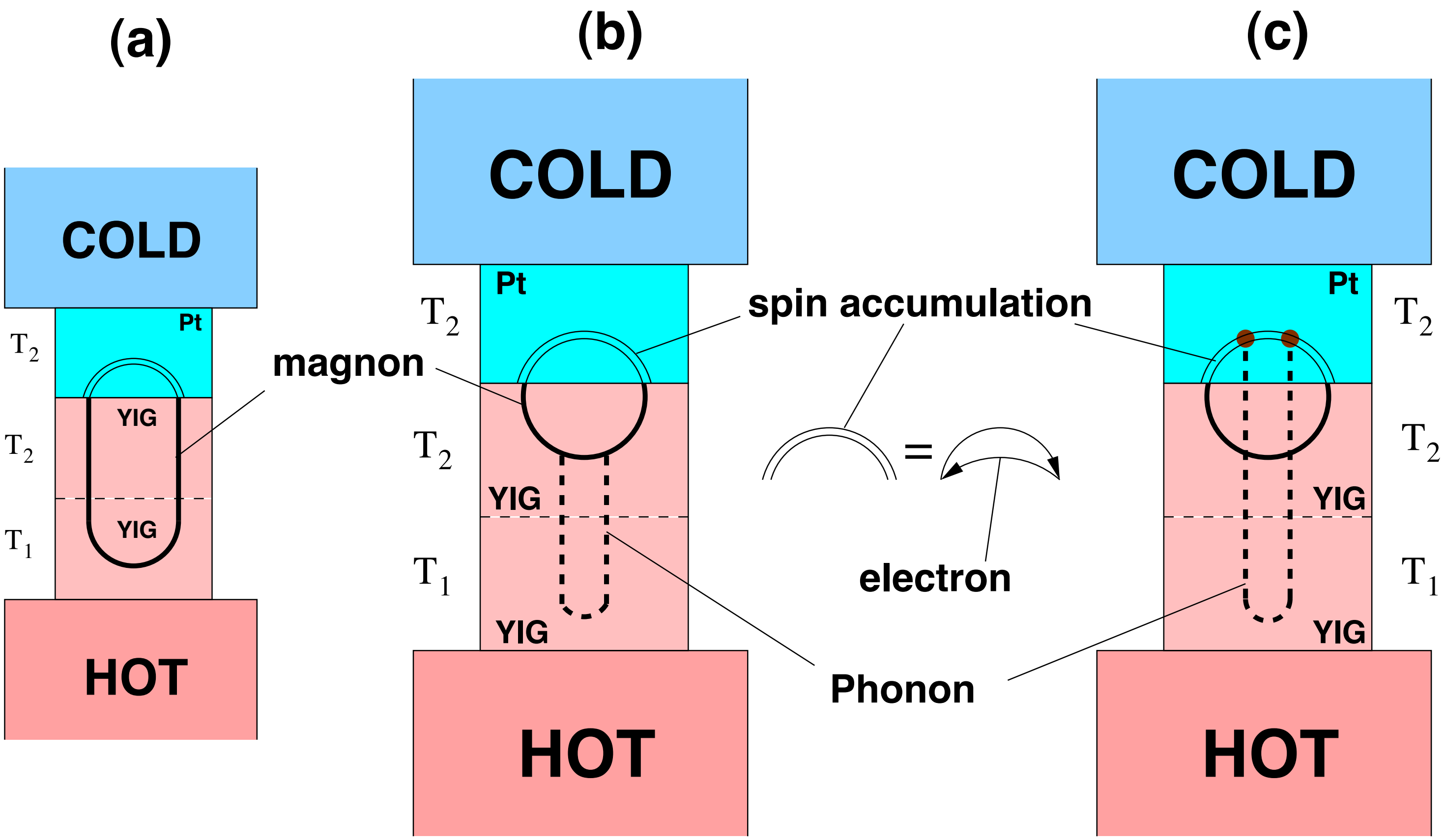


POSITIVE spin injection
@ colder side

NEGATIVE spin injection
@ colder side

Theory of Longitudinal SSE

KEY: Heat current flows through Pt terminal in case of the longitudinal SSE.



Electron-phonon coupling > Phonon-Magnon coupling,
Pt is heated by **phonon heat current** greater than YIG.

Summary:

1) Spin-Wave Spin Current,

<u>"Linear Response Theory of Spin-Wave Spin Current"</u>

"Magnetic insulator is a good spin current conductor!"

2) Spin Seebeck effect in a variety of systems,

<u>"Conversion among heat, electric and magnetic energies"</u>

↓

In the same way as Seebeck effect,
Spin Seebeck effect may be applied to a variety of
Energy saving devices!!