Heat transport by magnons, phonon-drag, and the Spin Seebeck Effect

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KITP, Concepts in Spintronics
Santa Barbara, CA, Oct. 2, 2013

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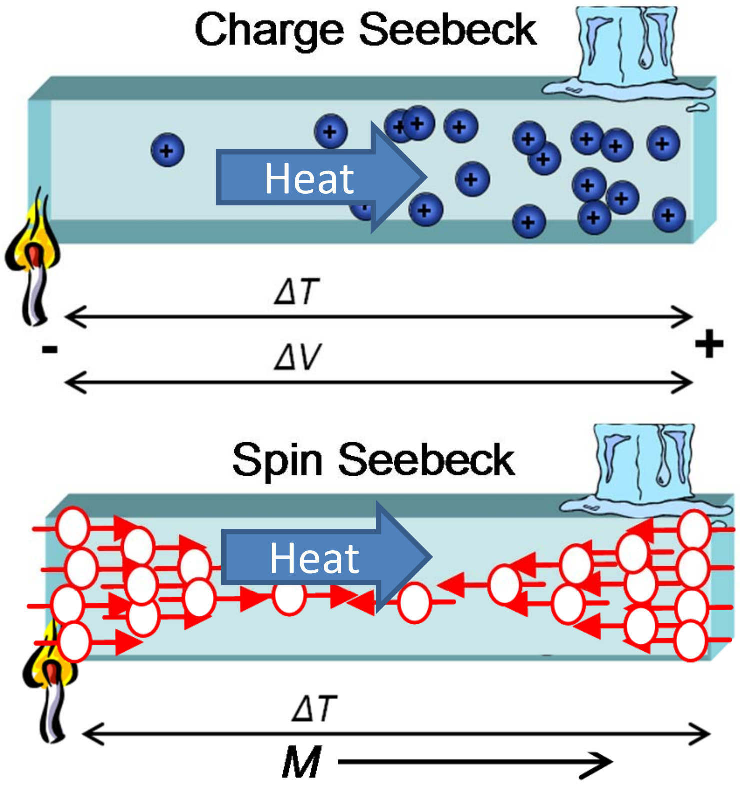
Spin-Seebeck effect definition

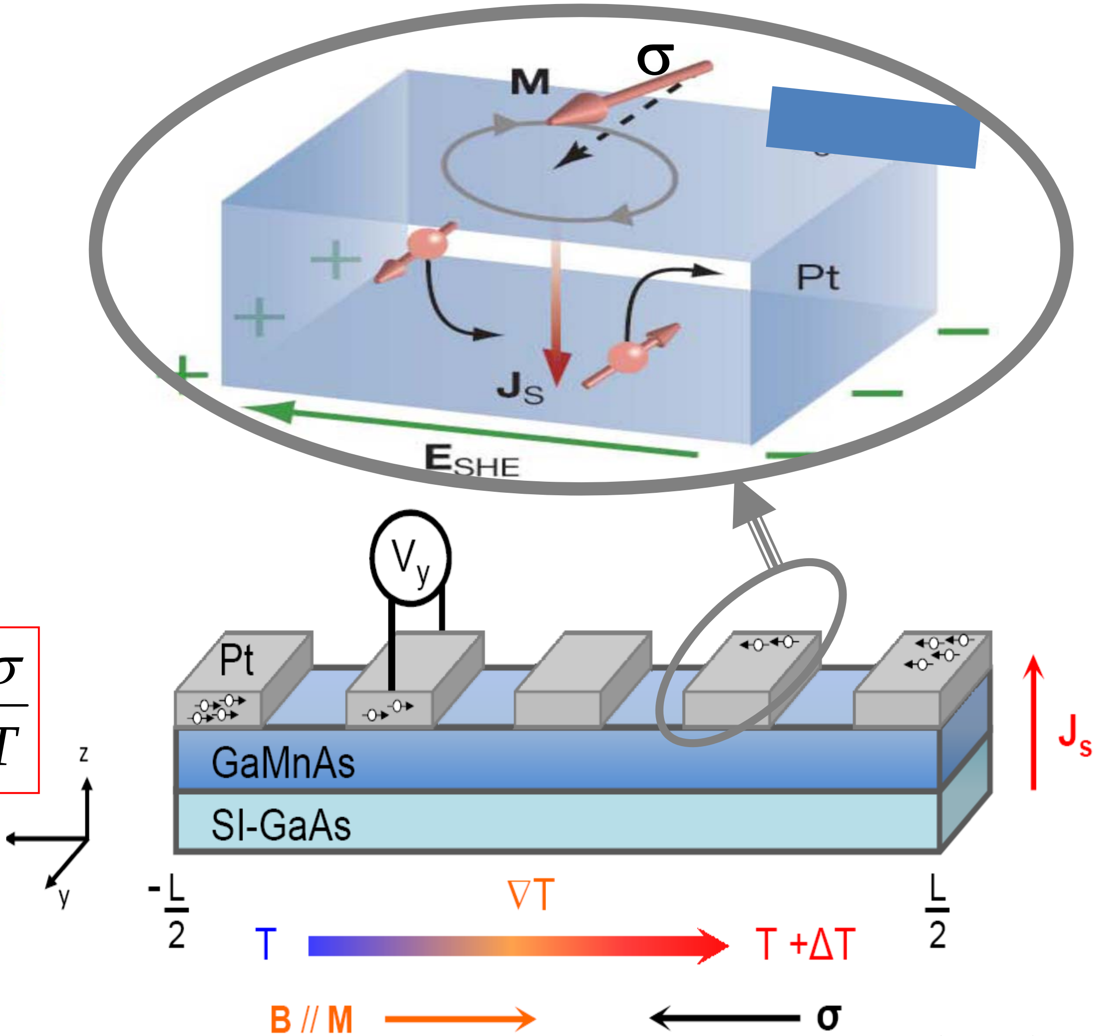


$$Spin\ Seebeck\ Coef. \equiv S_{xy} \propto \frac{\nabla_x \sigma}{\nabla_x T}$$

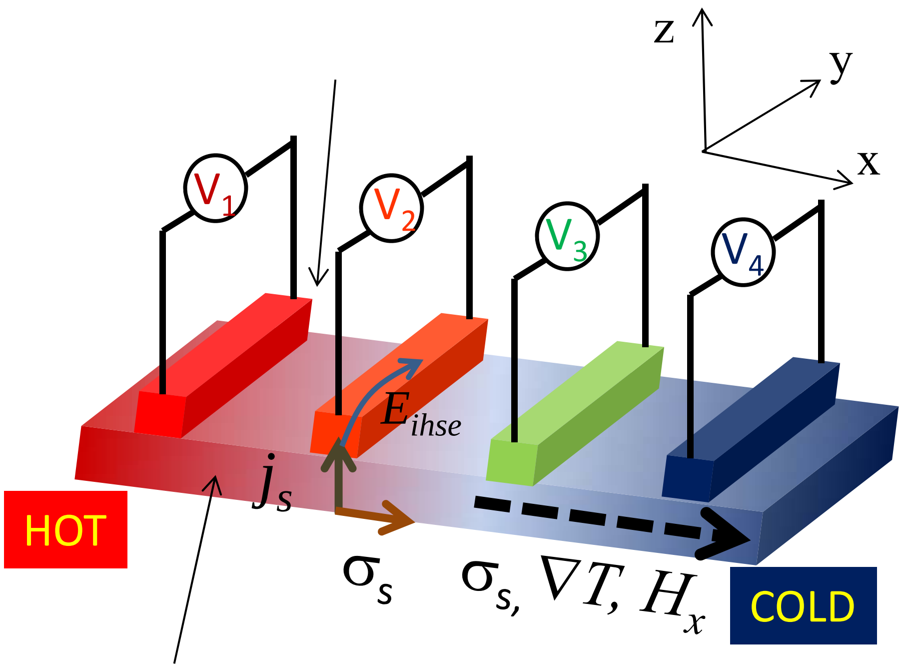
Grossly exaggerated for effect

Measurements rely on inverse spin-Hall effect:

$$\mathbf{E}_{ISHE} = D_{ISHE} \mathbf{J}_{\mathbf{S}} \times \boldsymbol{\sigma}$$



Transverse Spin-Seebeck Effect (TSSE)



Ferromagnet:

Metal: Pu *(Uchida & al, Nature, 2008)*

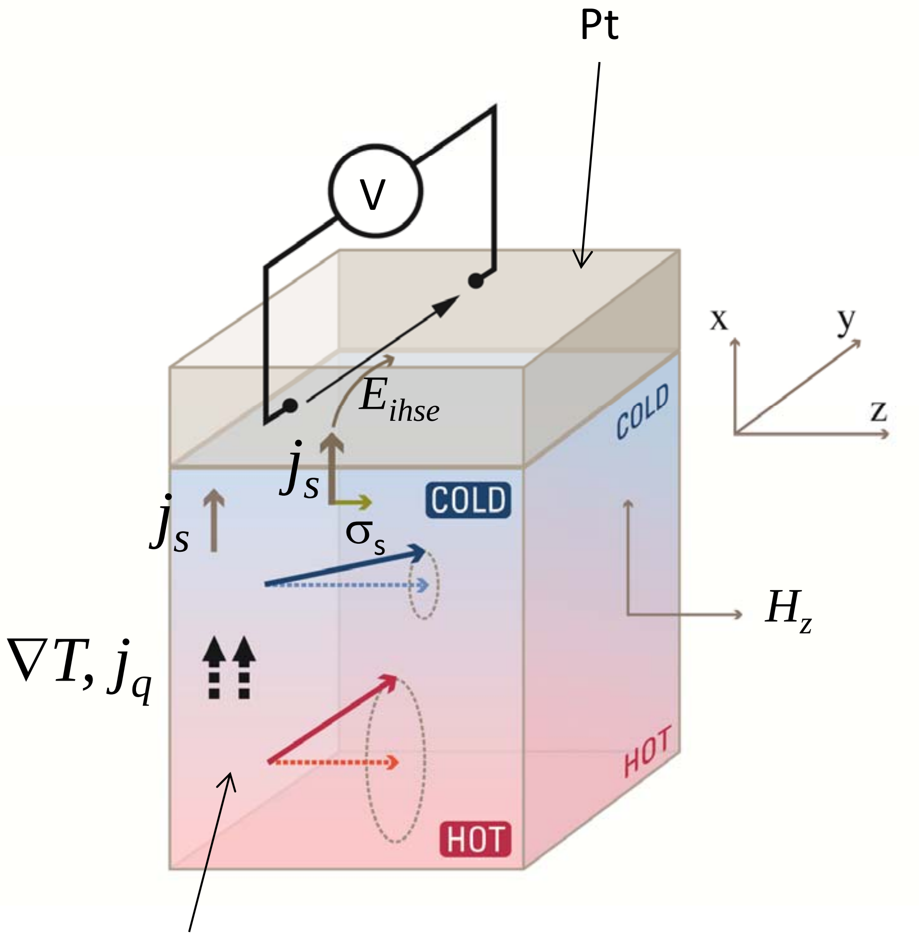
Semiconductor: GaMnAs

(Jaworski & al, Nat. Mater, 2010)

Insulator: YIG

(Uchida & al, Nat. Mater, 2010)

Longitudinal Spin-Seebeck Effect (LSSE)

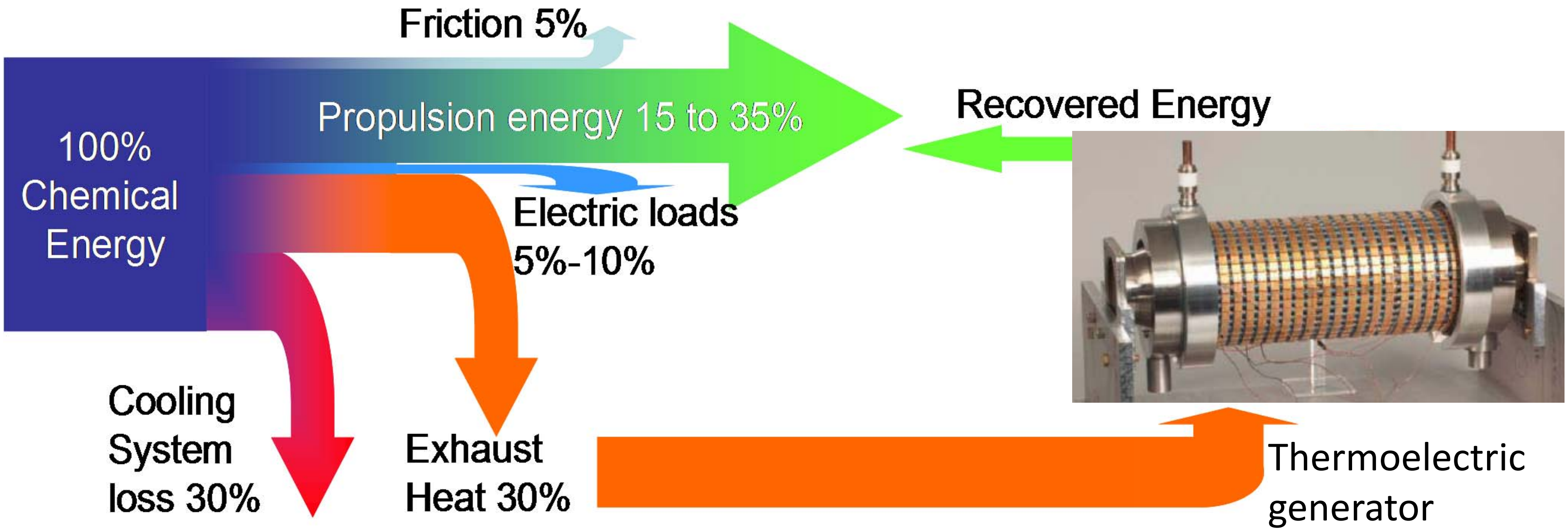


Ferromagnet:

Can only be an Insulator: YIG

(Uchida & al, APL2010)

Motivation: Solid State Heat Engines



Advantages:

- No moving parts
- Robust, infinite lifetime, no maintenance
- Very high power density (specific power) => **light weight**

Disadvantage:

- Lower efficiency

Heremans & al., Nature Nano (2013)

Structure of this lecture

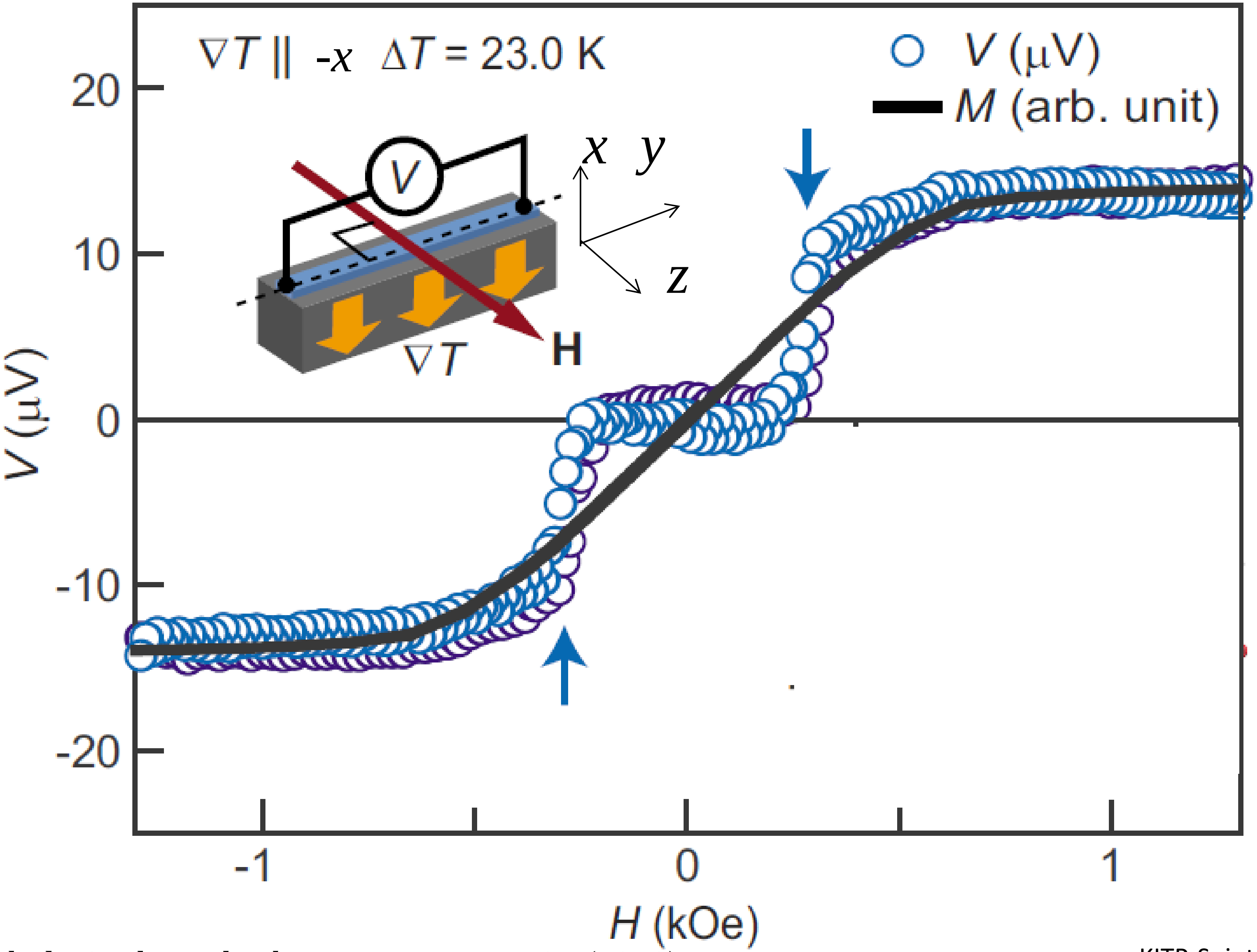
Emphasis on the thermal generation of the spin flux

1. Longitudinal spin Seebeck
    - In the Ferromagnet: Magnon thermal conductivity
2. Transverse Spin Seebeck effect
    - Non-local version of longitudinal spin Seebeck effect
    - GaMnAs: the role of phonons
    - Phonon drag
3. InSb, the giant spin Seebeck effect
4. Length Scales

1. Longitudinal Spin Seebeck Effect

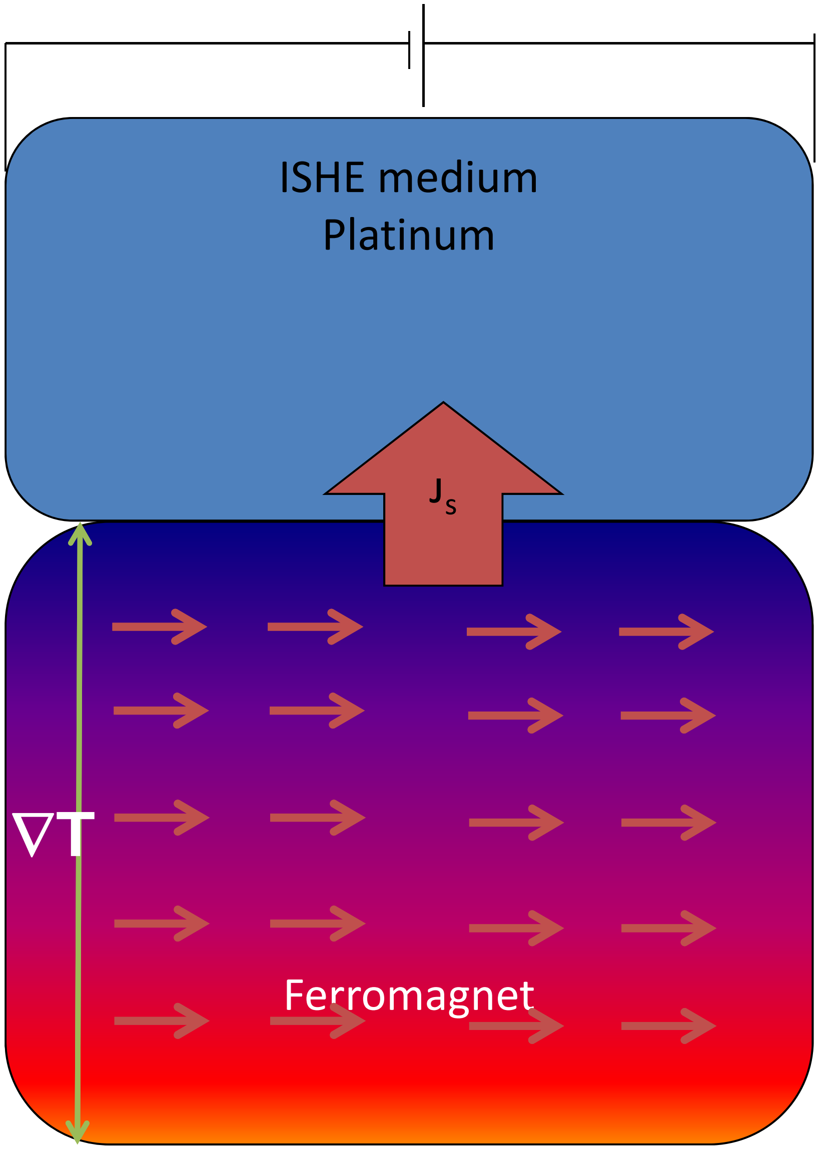
Pt/YIG

Longitudinal Spin-Seebeck Effect YIG/Pt



K.Uchida & al. Appl. Phys. Lett. ***97****, 172505 (2010)*

Understanding the Longitudinal Spin-Seebeck effect



1. ∇T drives the magnons out of thermal equilibrium:

1.1 **magnon thermal conductivity**

1.2 phonon-drag

2. Spin-torque results from magnons striving back to equilibrium

3. Net spin flux diffuses into Pt

4. Spin-orbit interactions in Pt convert $J_S \Rightarrow E_{ISHE}$

- *S. Hoffman & al., arXiv1304.7295v (2013)*
- *J. Xiao et al., PRB **81**, 214418 (2010).*
- *H. Adachi, J.-I. Ohe, S. Takahashi, and S. Maekawa, PRB **83**, 094410 (2011).*
- *H. Adachi et al., APL. **97**, 252506 (2010).*
- *K. Uchida et al., SSC **150**, 524 (2010).*

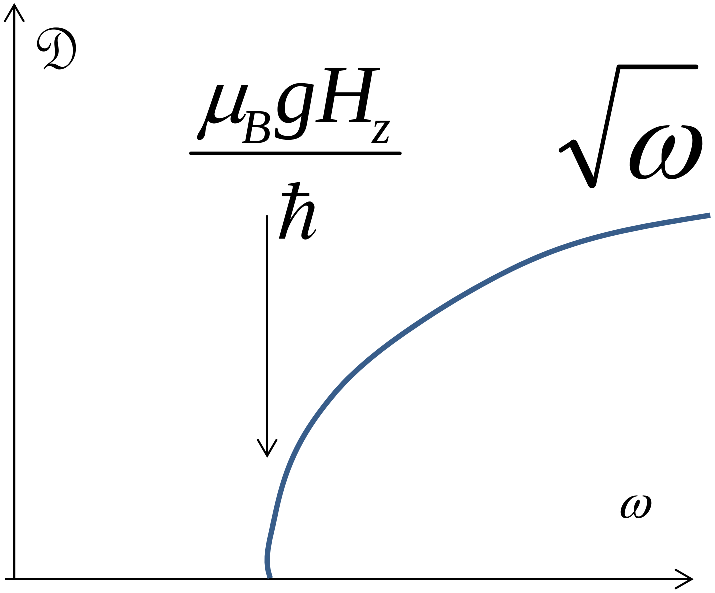
Magnon density of states $\mathcal{D}(\omega)$, ferromagnets

Kittel: $$\boxed{\hbar\omega_k = \mu_B g H_z + 2JSa^2k^2}$$

Magnons have only a single polarization for each value of k

Number of magnon states of frequency between ω and $\omega+d\omega$

$$\boxed{\mathcal{D}(\omega) = \begin{cases} 0 & , \quad \omega < \mu_B g H_z/\hbar \\ \dfrac{1}{4\pi^2}\left(\dfrac{\hbar}{2JSa^2}\right)^{3/2}\sqrt{\omega}, & \omega > \mu_B g H_z/\hbar \end{cases}}$$



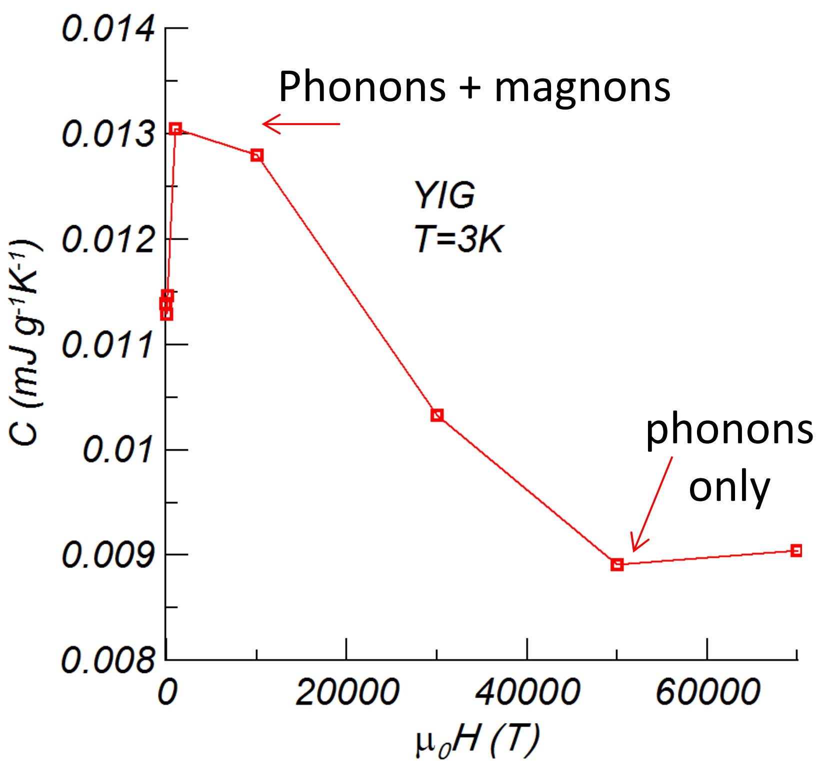
Magnetic fields can freeze out magnons, ~ 10^{-4}eV/T or 1.3 K / T

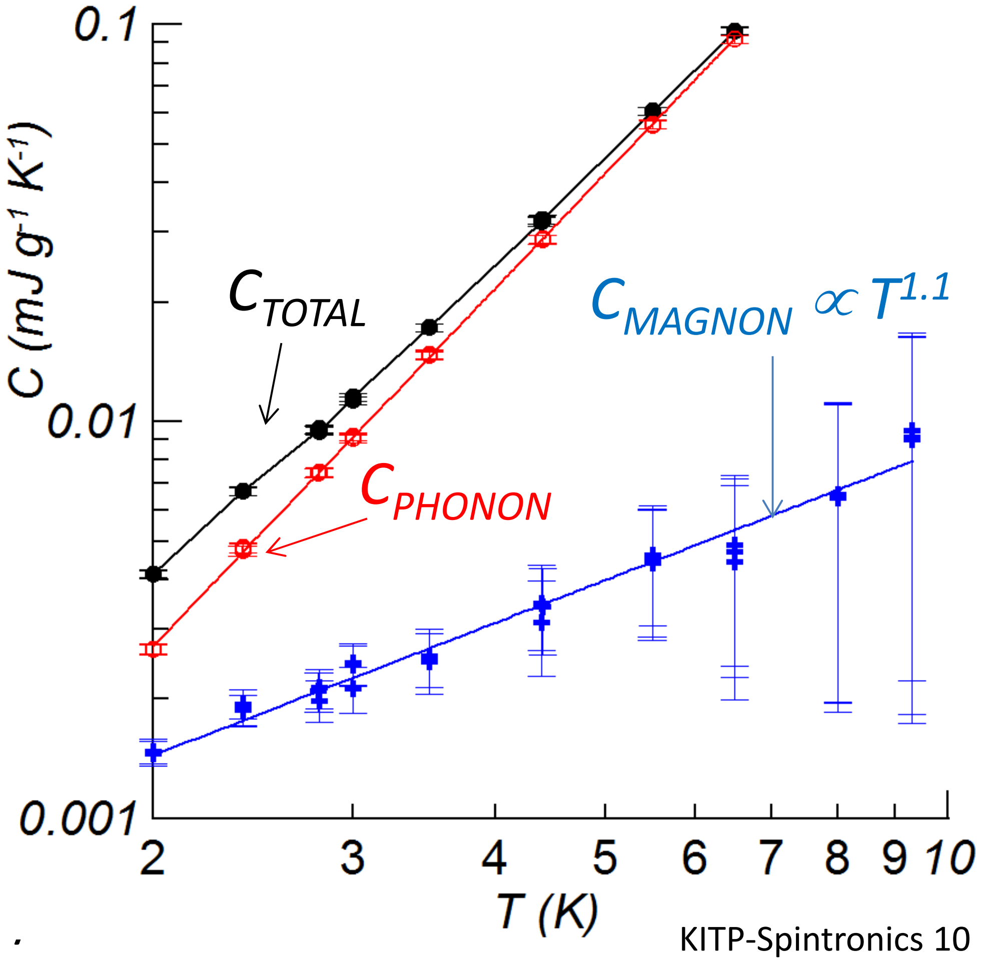
$$U(T) = \int_0^\infty \hbar\omega\mathfrak{D}(\omega)\, f_0(\omega)\, d\omega$$

Magnon specific heat

$$C_{MAGNON}(T) \equiv \frac{dU}{dT} = 0.113\left(\frac{k_B T}{2JSa^2}\right)^{3/2} \mathbf{exp}\left(\frac{E_{gM}}{k_B T}\right)$$

Assuming phonons and magnons are independent, one can assume additivity



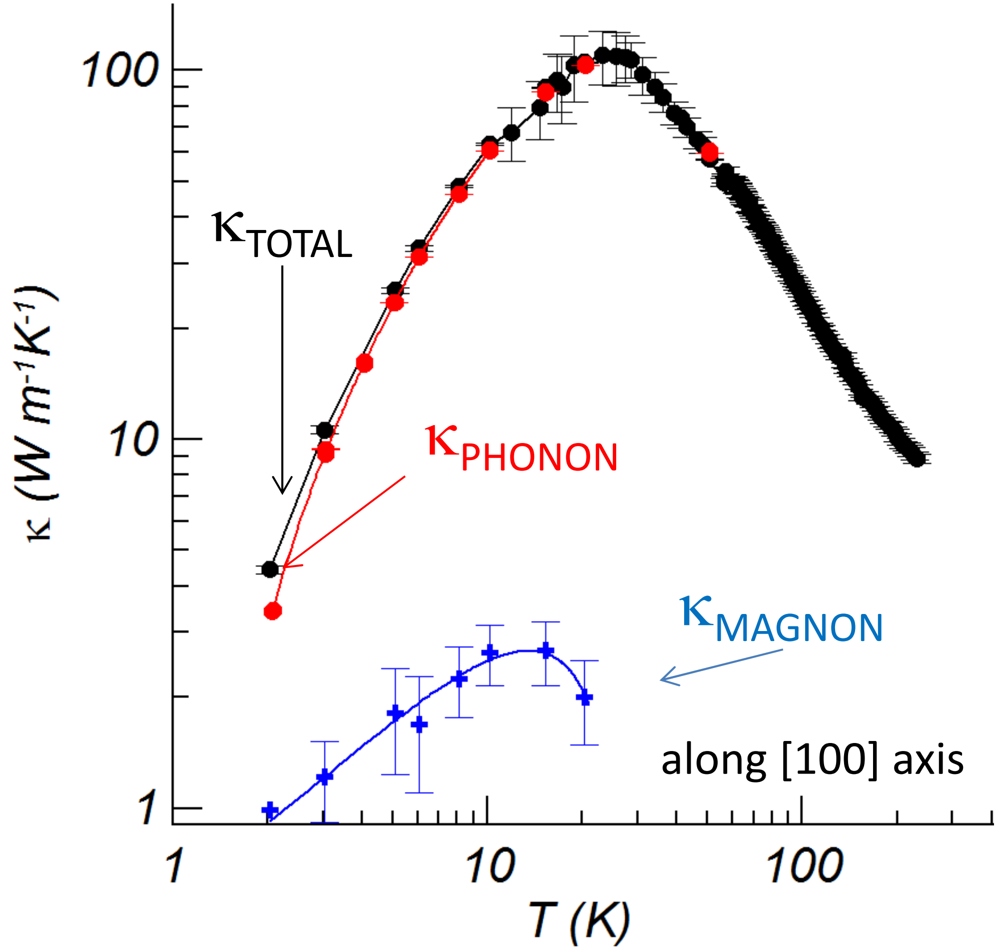


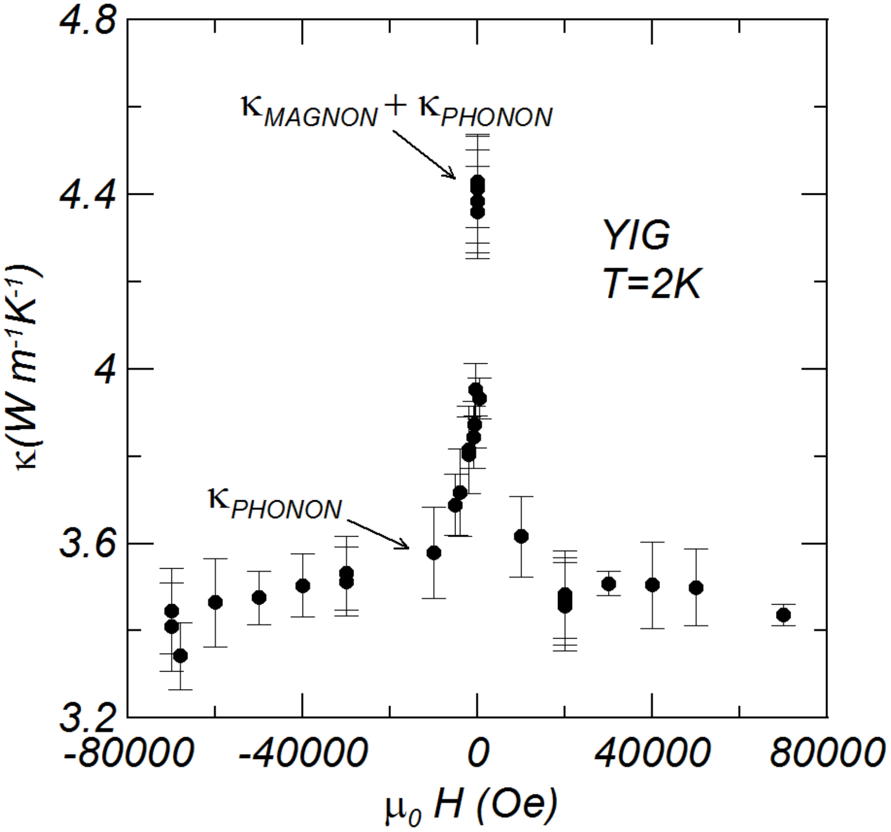
Approximate: magnons and phonons h

Magnon thermal conductivity in YIG

$$\kappa_{MAGNON} \approx \frac{1}{3} C_{MAGNON} v_{MAGNON} \ell_{MAGNON}$$

Same idea:
freeze out magnons by applying magnetic field





$$\boxed{j_Q = \kappa_{MAGNON} \nabla T \propto \frac{k_B T}{\hbar} . j_S}$$

Douglass, Phys. Rev. ***129****, 1132 (1963).*
Pan & al., arXiv1302.6739v1
Boona & al., unpublished

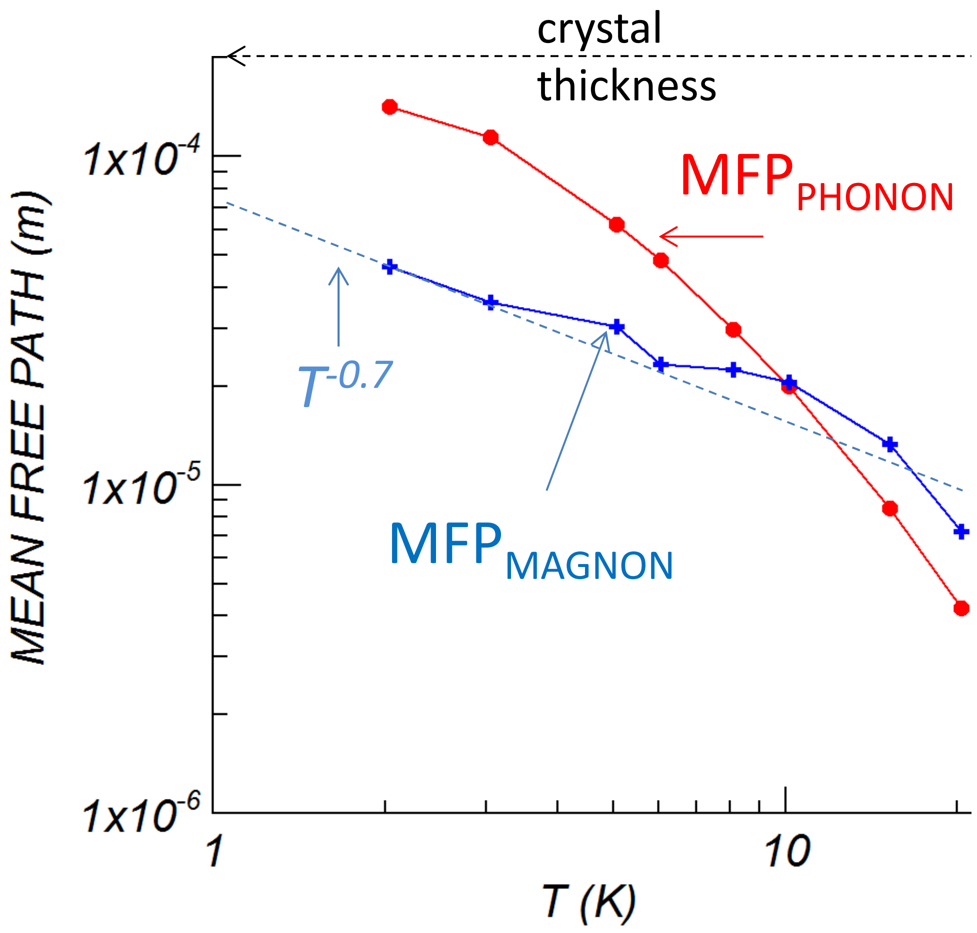
Magnon and phonon mean free paths (YIG)

8500 ms^{-1}

$$\kappa_{MAGNON} \approx \frac{1}{3} C_{MAGNON}\, v_{MAGNON}\, \ell_{MAGNON}$$

$$\kappa_{PHONON} \approx \frac{1}{3} C_{PHONON}\, v_{PHONON}\, \ell_{PHONON}$$

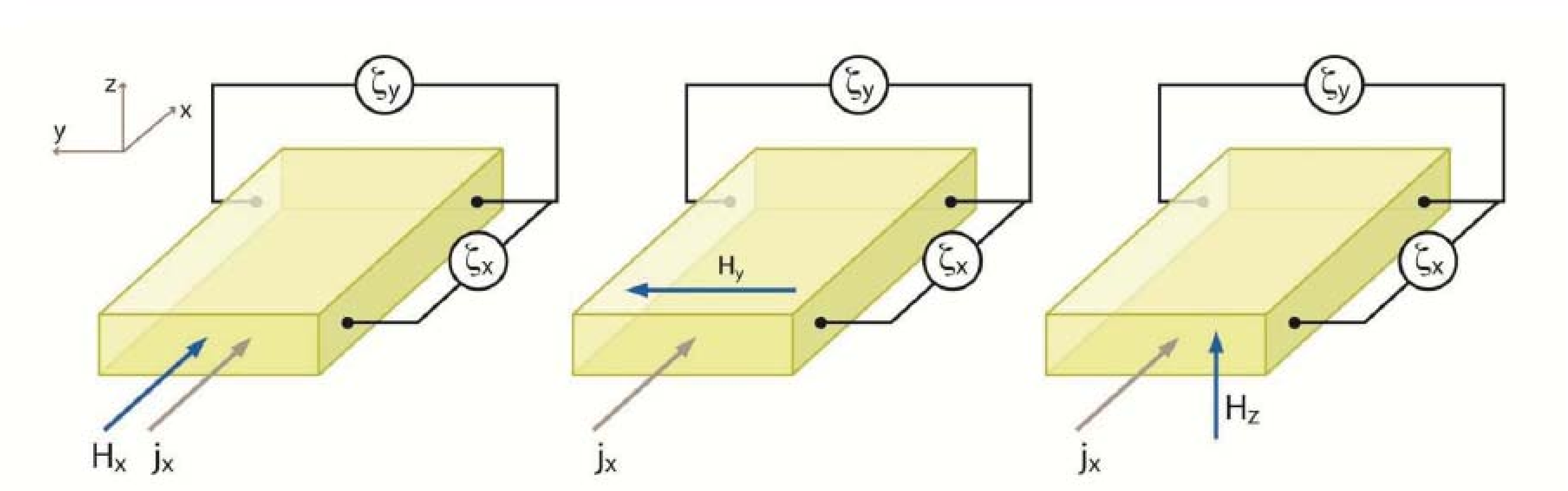
5000 ms^{-1}



In YIG at low temperature the magnon "Energy mean free path" ~ 5 to 50 μm

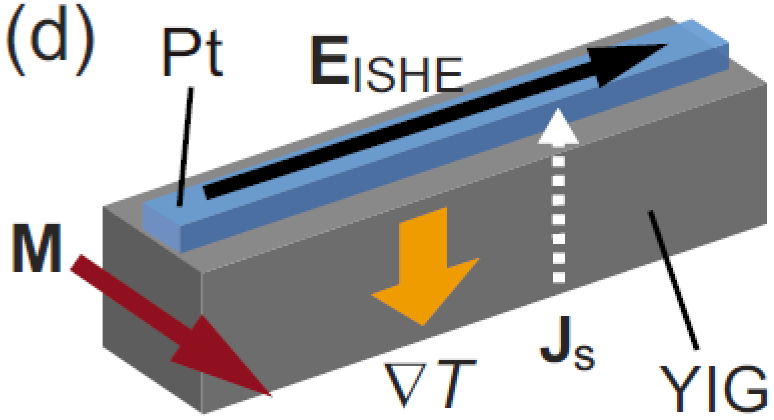
Boona & al., unpublished

What can go wrong experimentally?
Thermomagnetic & Galvanomagnetic Effects



- Anisotropic magnetoresistance, planar Hall effect
- Anisotropic magneto-thermopower, planar Nernst effect
- Hall effect (Ordinary, anomalous)
- Nernst effect (Ordinary, anomalous)

Longitudinal Spin-Seebeck Effect ONLY on YIG/Pt



The planar Nernst effect has exactly the same symmetry as the longitudinal spin-Seebeck effect

LSSE measurements impossible on electrically conducting ferromagnets

2. Transverse Spin Seebeck Effect

- Lifts the requirement that the spin-polarized material be electrically insulating

Ferromagnets:
Metal: Pu *(Uchida & al, Nature, 2008)*
Semiconductor: GaMnAs *(Jaworski & al, Nat. Mater, 2010)*
Insulator: YIG *(Uchida & al, Nat. Mater, 2010)*

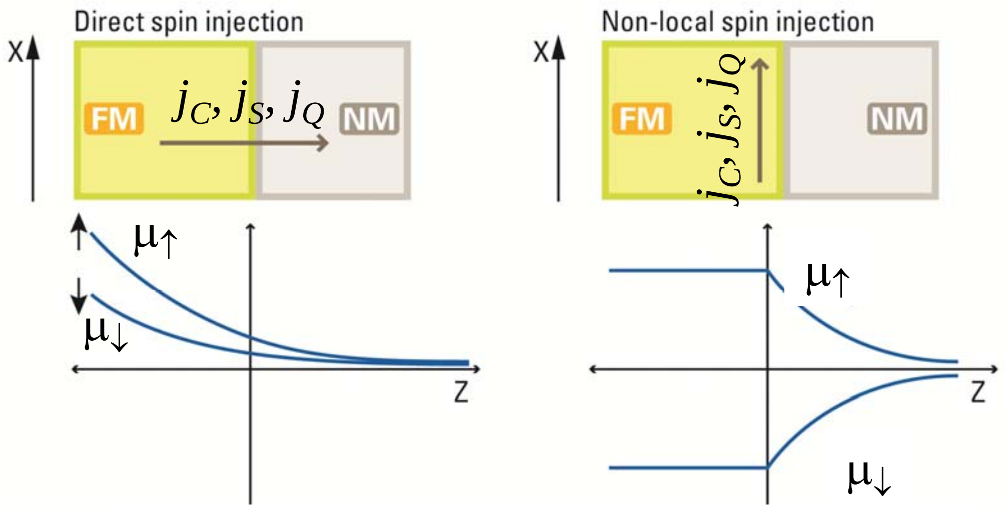
No exchange coupling:
Semiconductor with large s/o interactions: InSb *(Jaworski & al, Nature, 2012)*

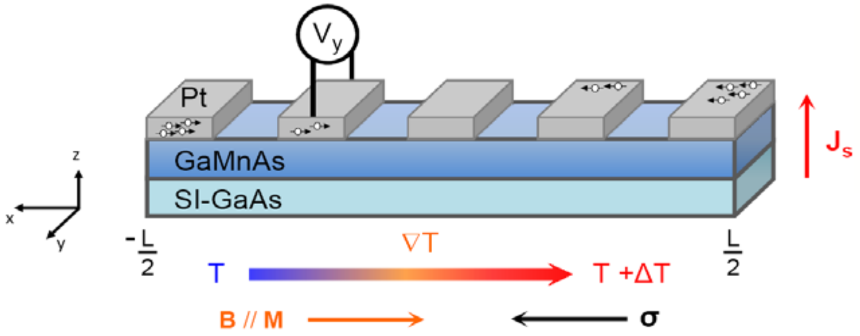
- Unresolved issue: the length scale

Local vs non-local spin injection

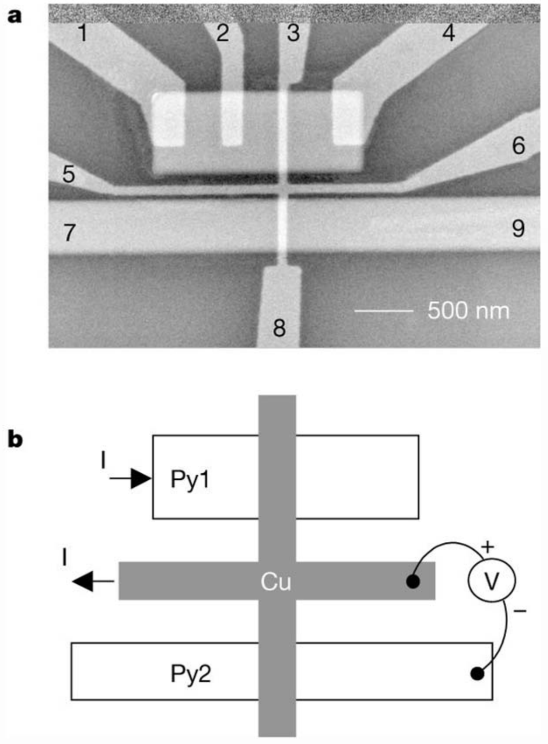
Non-local electrical spin injection:

- spin-polarized charge current is driven by an applied electric field.
- spin current parallel to a charge current
- => spin current **diffuses** from the ferromagnet into the normal metal.





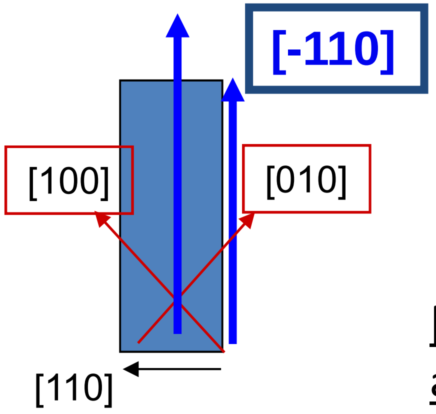
Equivalent for electrical spin injection:



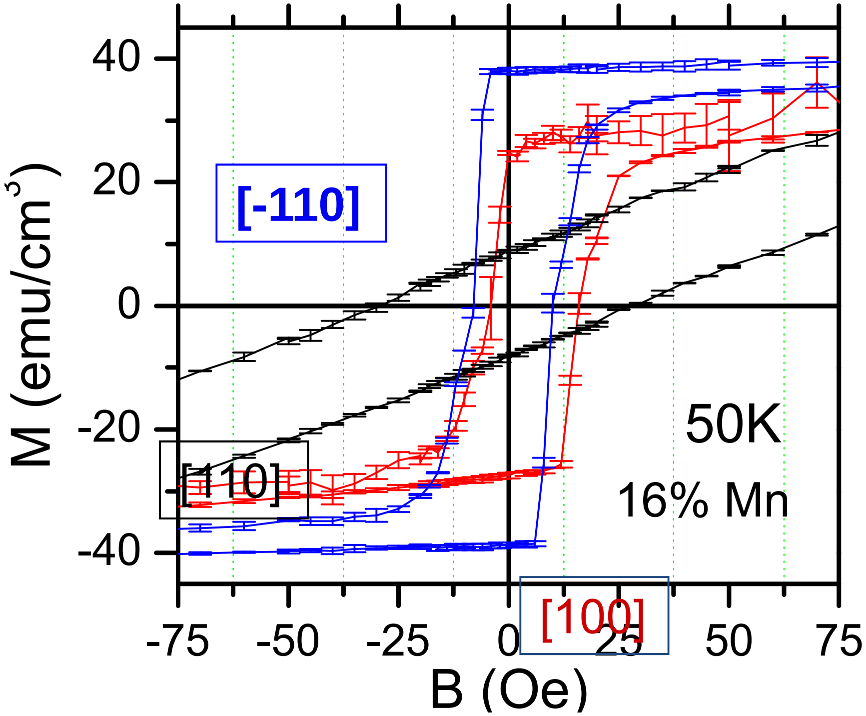
F. J. Jedema, A. T. Filip & B. J. van Wees, Nature ***410*** *345 (2001)*

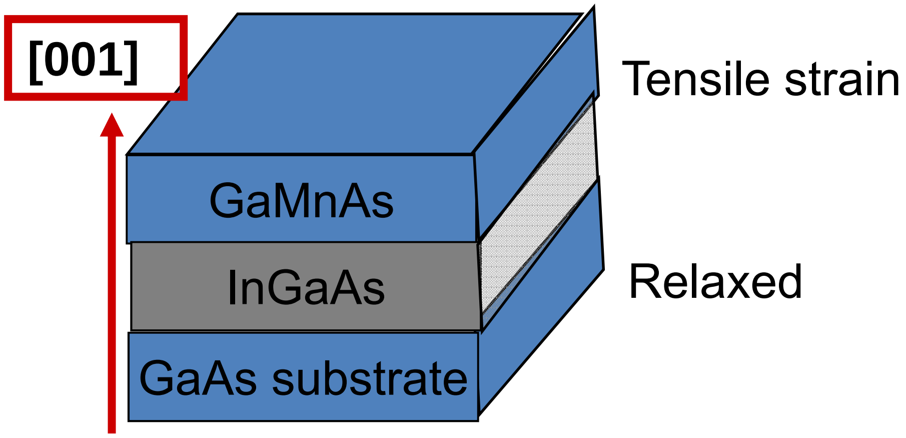
***GaMnAs** In-plane easy axes*

Mn content 7-18%

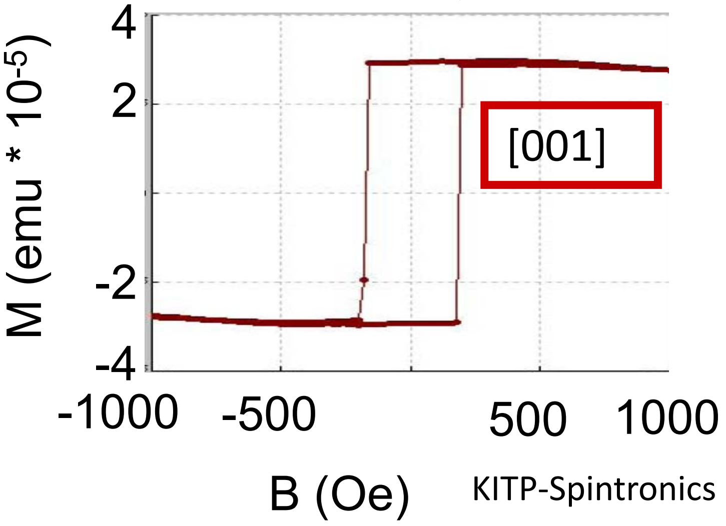


[-1,1,0] & [100] are easy axes

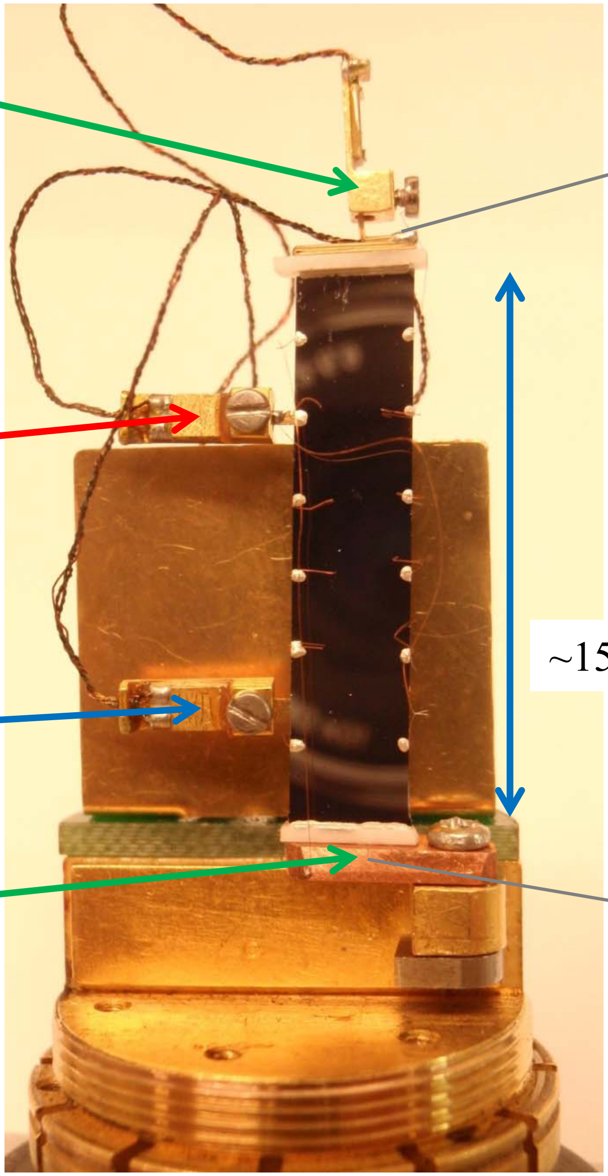




30 nm thick, 6% Mn



GaMnAs: Measurement setup



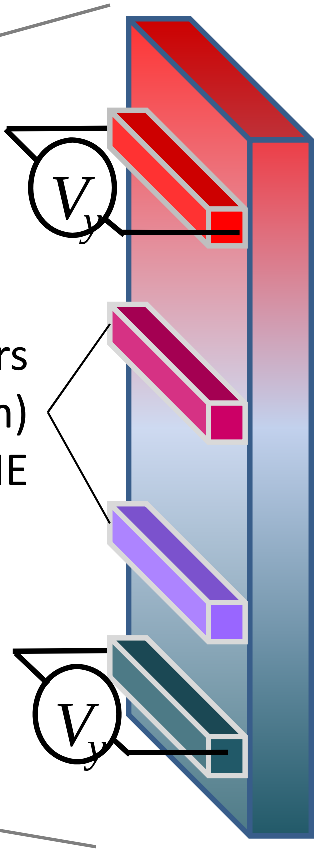
Heater

T_{Hot}

thermometry:
cernox
resistors

T_{Cold}

Heat Sink



Pt bars
(10 nm)
ISHE

GaMnAs
(30-100nm)

QD PPMS brochure

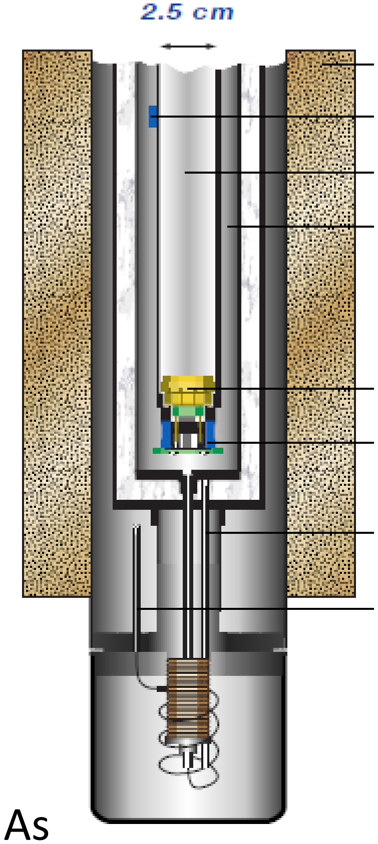
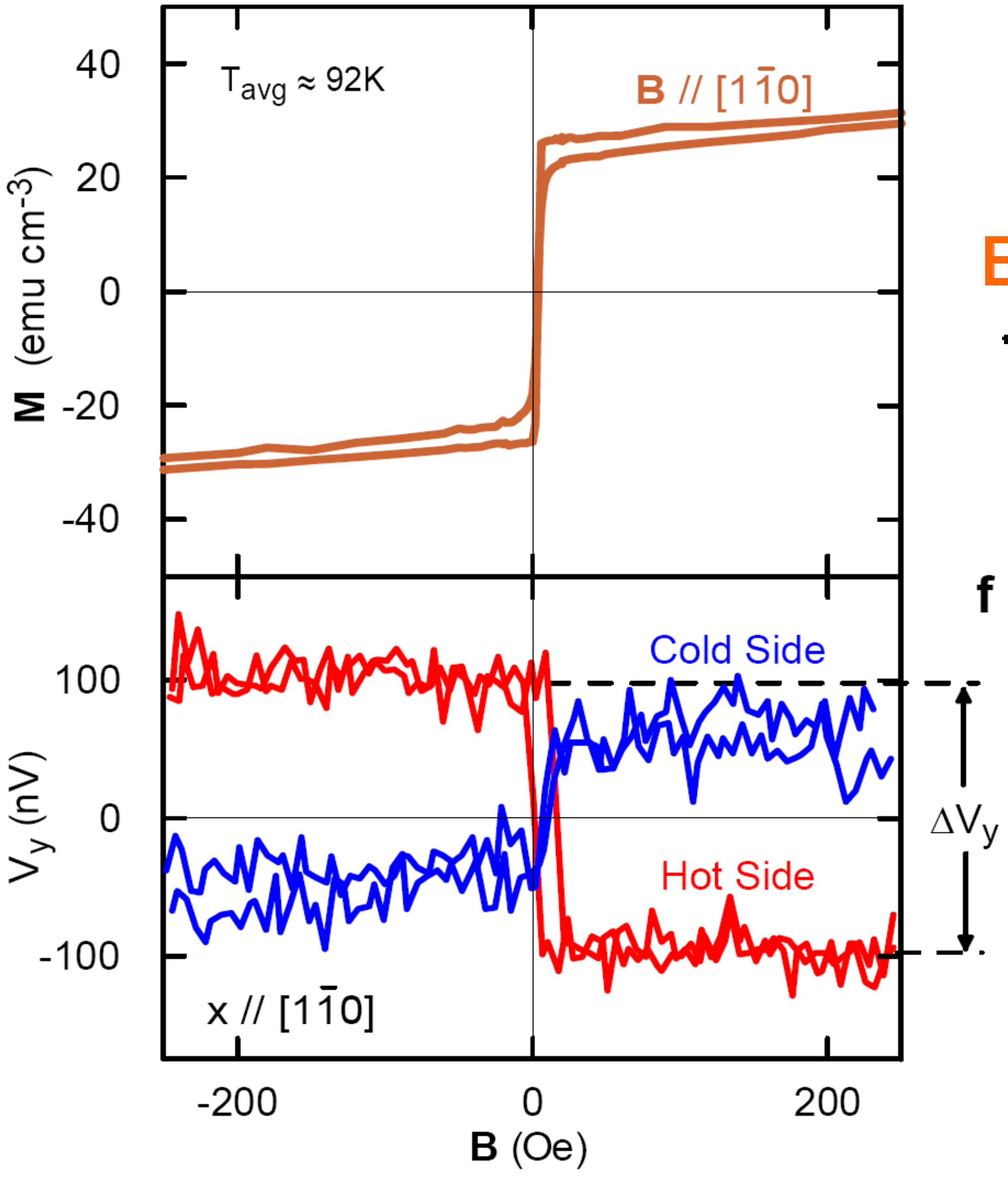
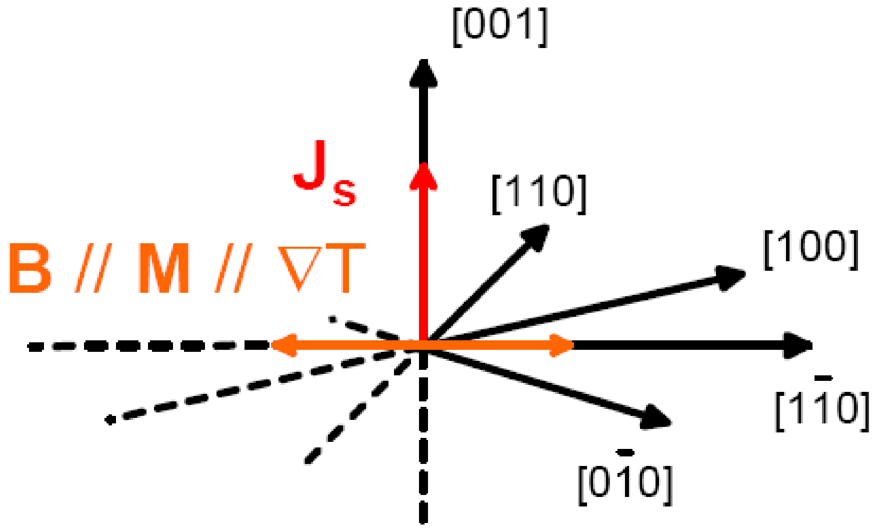


Image taken with thermometry attached (2nd or 3rd run)
1st – 2nd run read voltage on Cu wires

B // ∇T // easy axes





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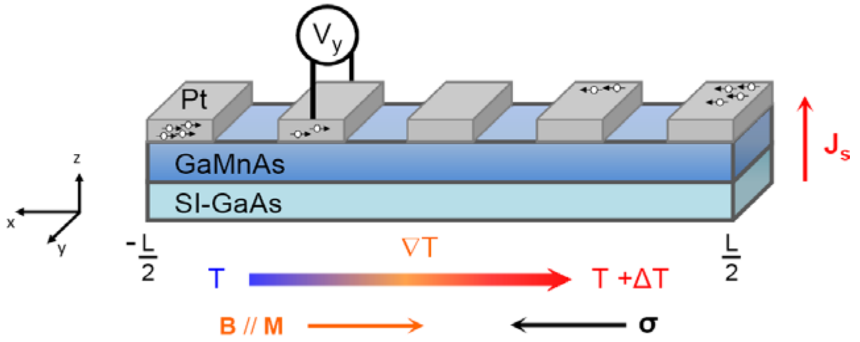
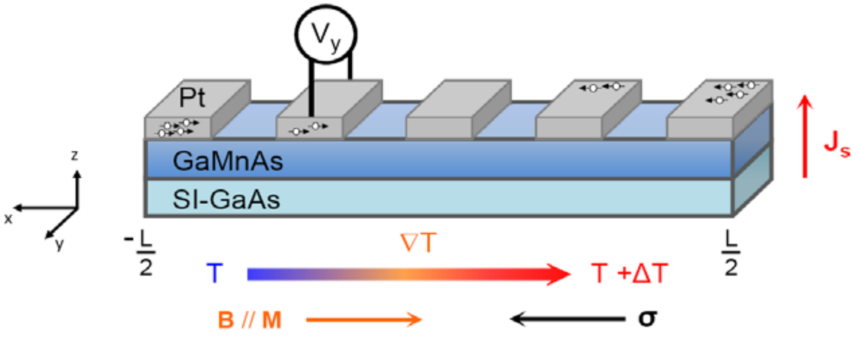
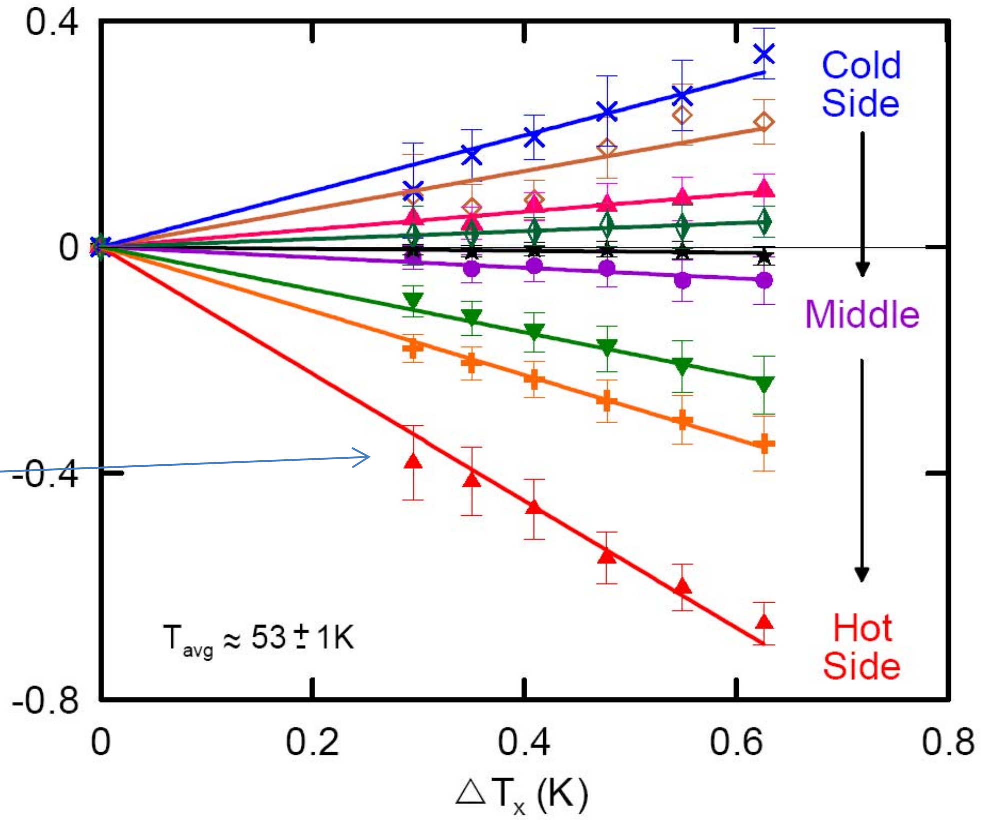


Jaworski & al, Nat. Mater, 2010

Dependences on temperature gradient





1. Dependence on temperature gradient is linear

=> can assign a "Seebeck coefficient" to the slope

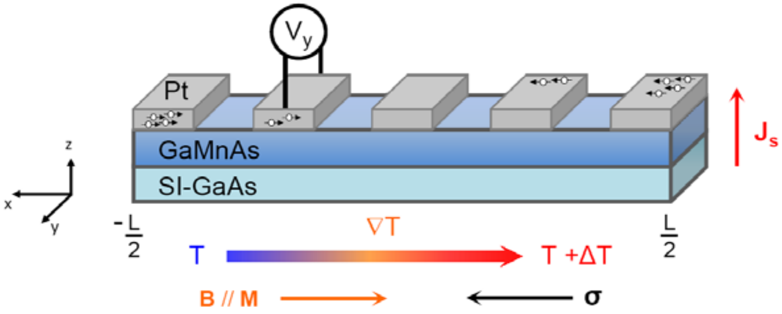
2. Dependence on strip position is totally unusual for transport coefficient

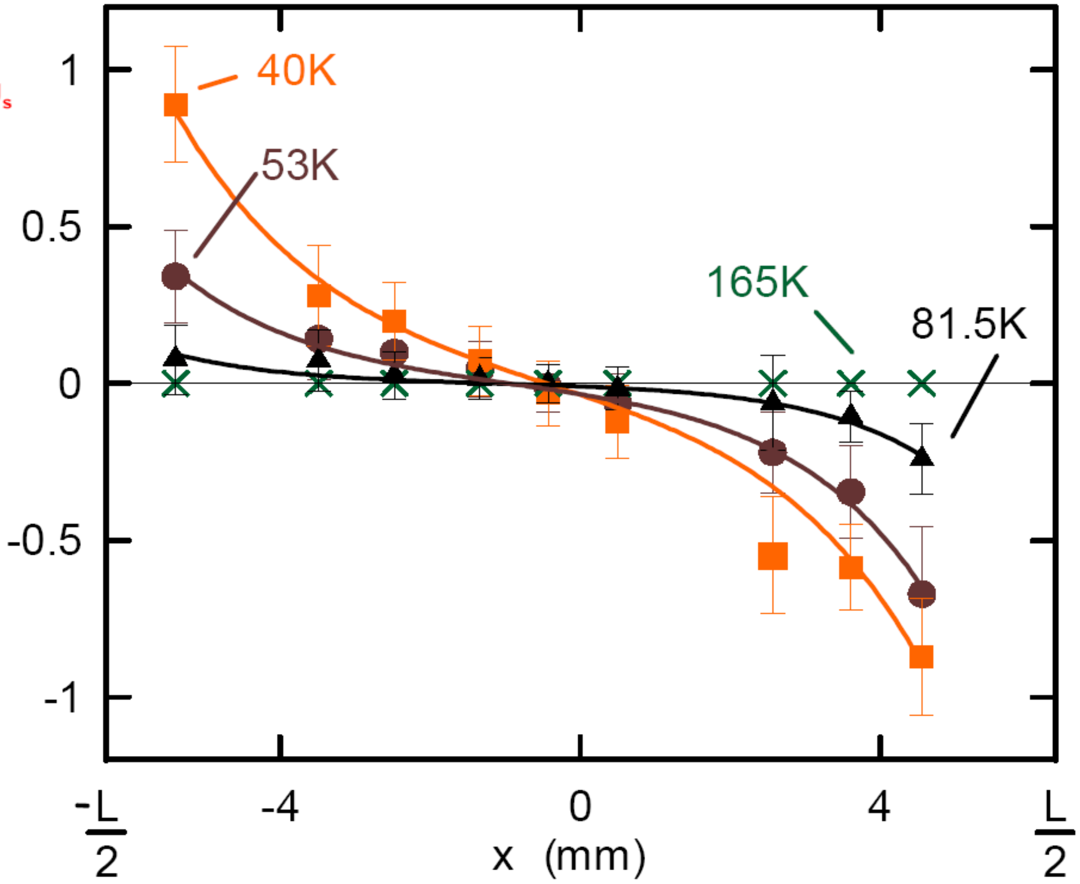
Contrast with charge-Seebeck between strips

$$S_{XY} \equiv \frac{E_Y}{\nabla_X T} = \frac{V_Y}{\Delta T_X}\frac{L}{2w}$$

$$\alpha_{XX} = \frac{E_X}{\nabla_X T} = \frac{V_X}{\Delta T_X}$$

Position dependence of Spin-Seebeck S_{xy}



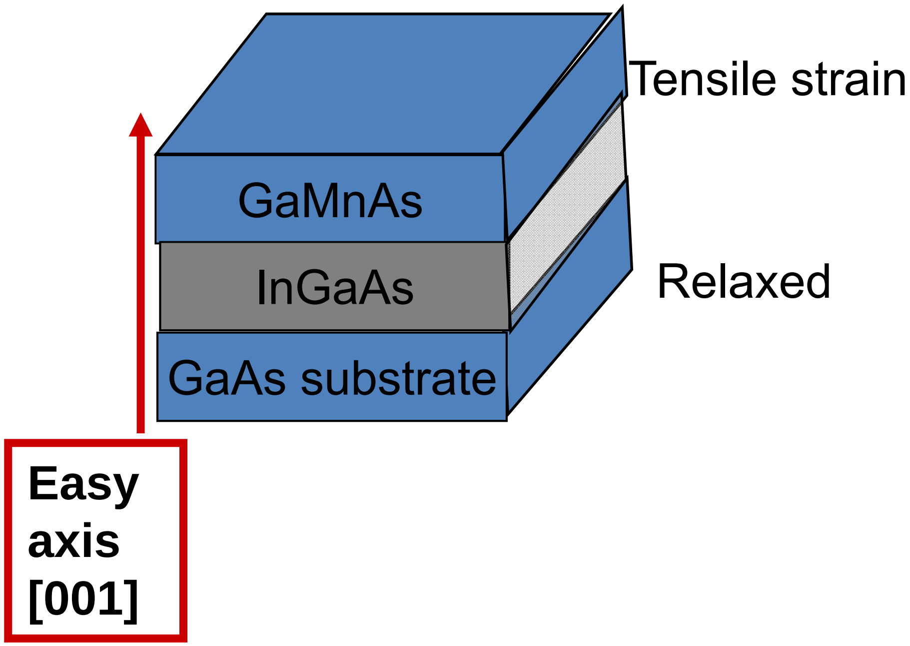


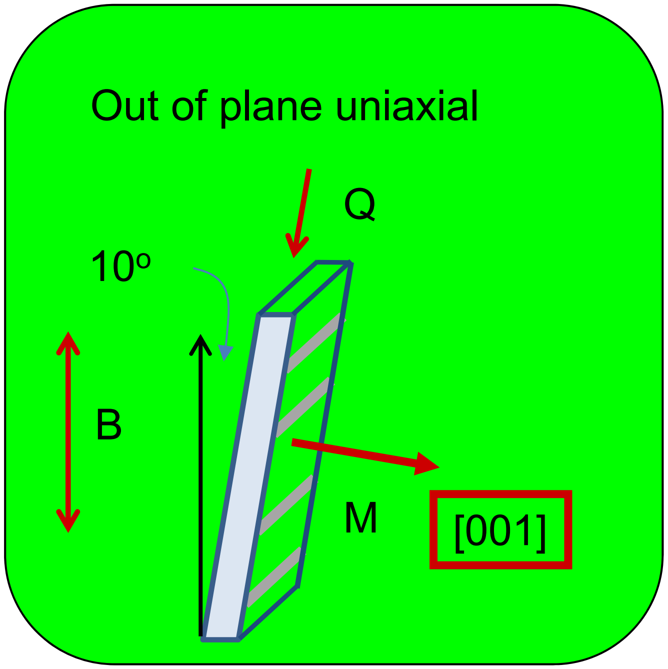
A skewed and off-center *sinh(x)* function, with a characteristic length scale of 4 - 6 mm

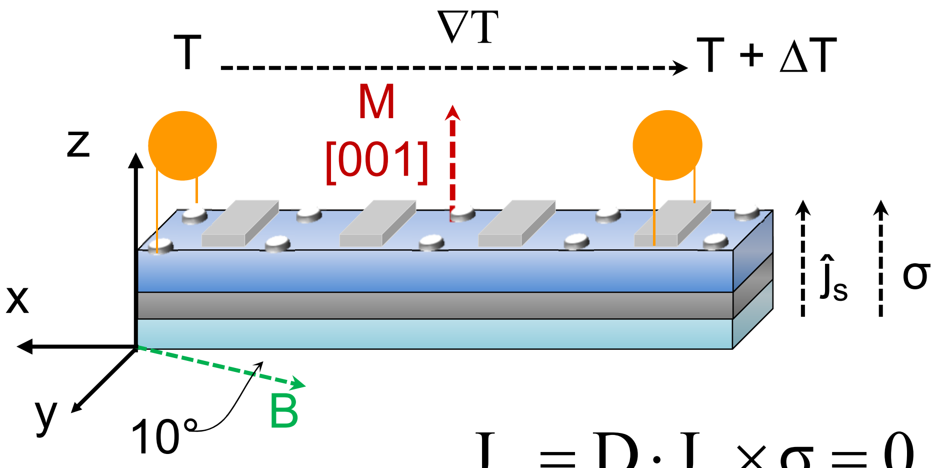
$$S_{XY}(x) \approx -\alpha \sinh[\beta(x - \frac{L}{2} - x_0)]$$

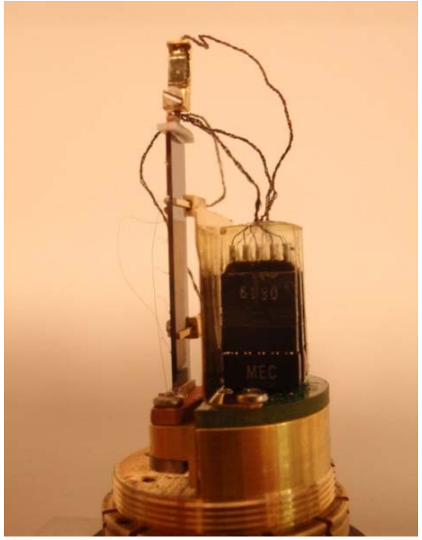
Similar to T(magnons) in *D. J. Sanders and D. Walton, Phys. Rev. B* ***15*** *1489 (1977)*

Easy axis out-of-plane





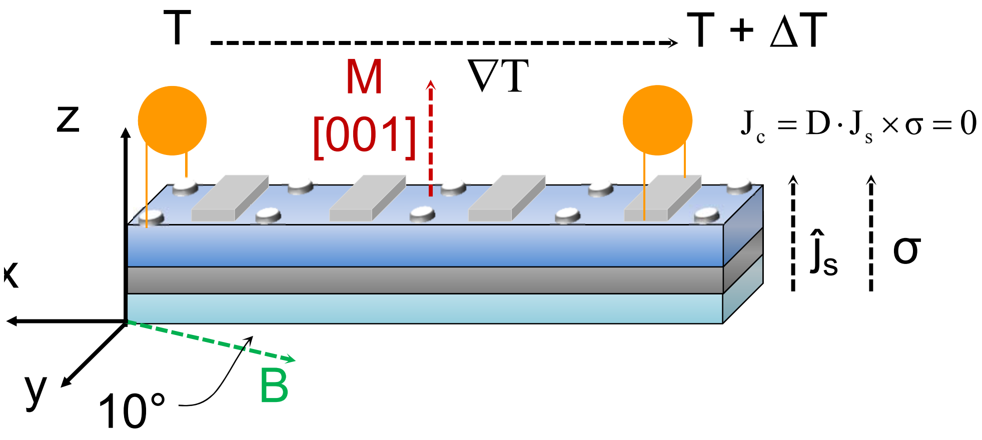


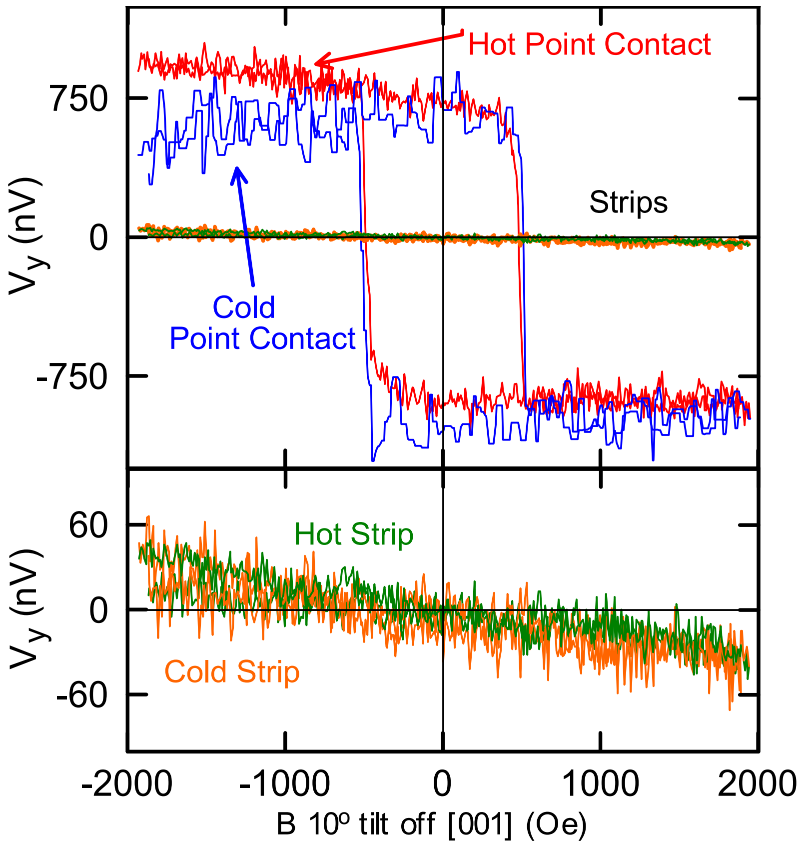


$$J_c = D \cdot J_s \times \sigma = 0$$

=> We expect no signal

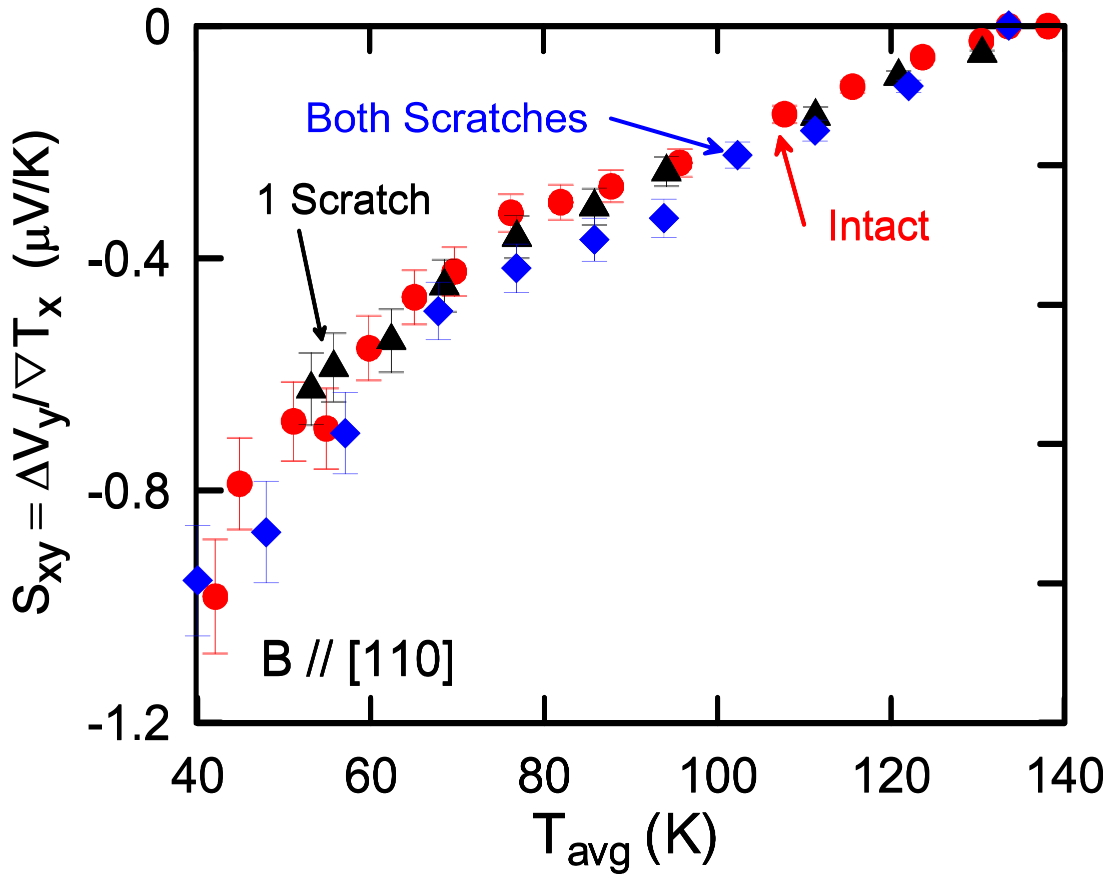
Transverse Nernst-Ettingshausen effect

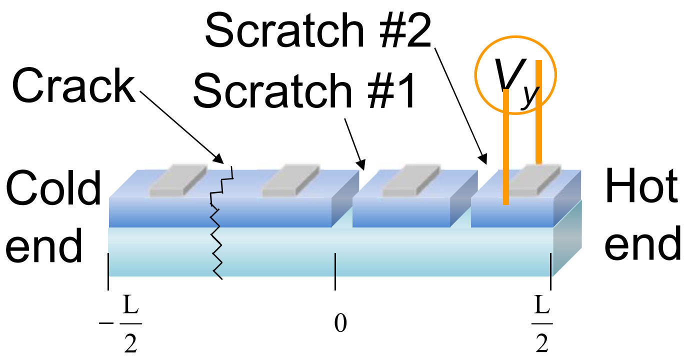




- Indium point contacts give large signal
  - True Nernst signal
  - Has NO spatial dependence
- The Pt strips give no signal
  - The Pt strips short out the Nernst signal
- We are not measuring parasitic Nernst effect on Pt strips

Spin Seebeck is NOT due to spin current along ∇T





- No change in signal

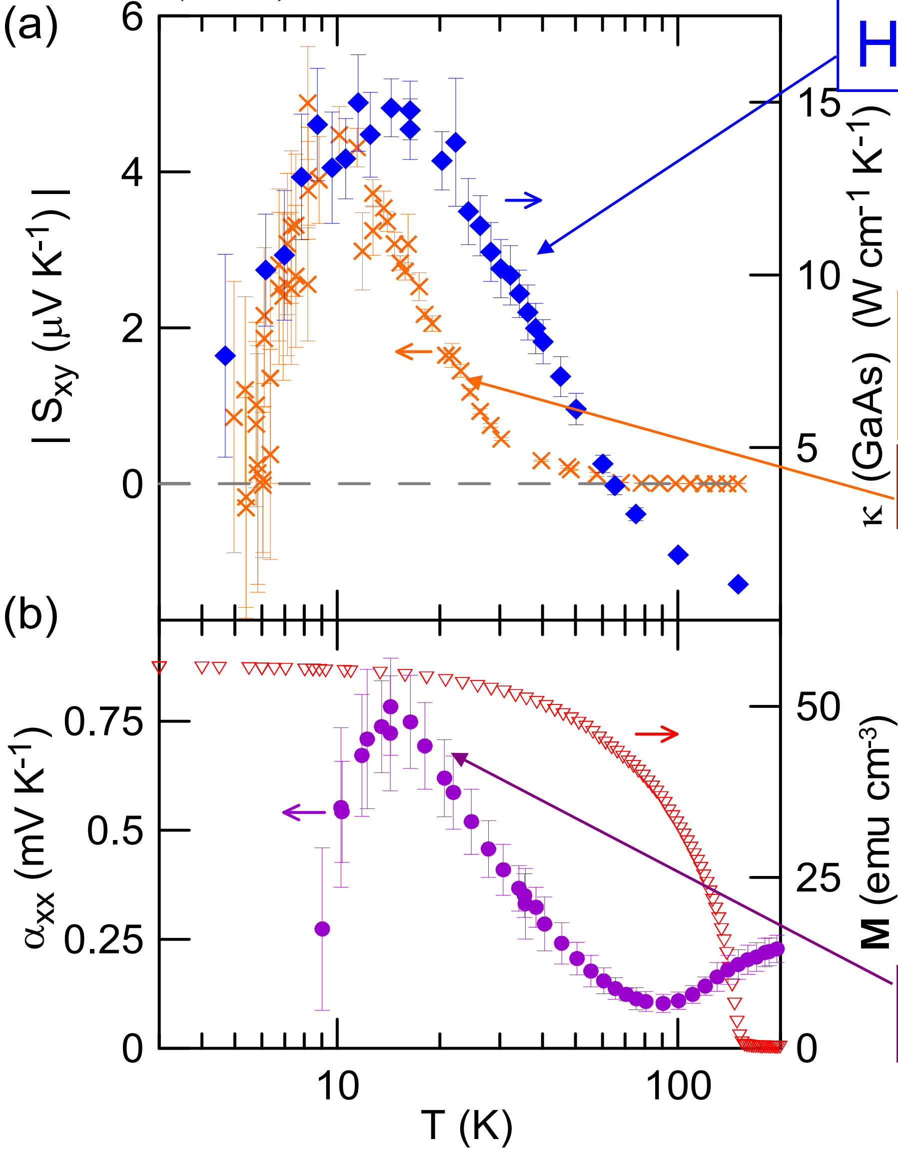
- Spin-Seebeck does not result from a macroscopic spin-current **in** the plane.

- The substrate, not the film, carries the mm-range information

The Maekawa-Adachi Anzats: it's the phonons in the subtrate that are the driving force (*Adachi, Appl. Phys. Lett.* ***97*** *252506 (2010)*)

Phonon-drag in GaAs substrate of GaMnAs

Jaworski et al., Phys. Rev. Lett. ***106*** *186601 (2011)*



Thermal conductivity of substrate

High

Low

Spin Seebeck

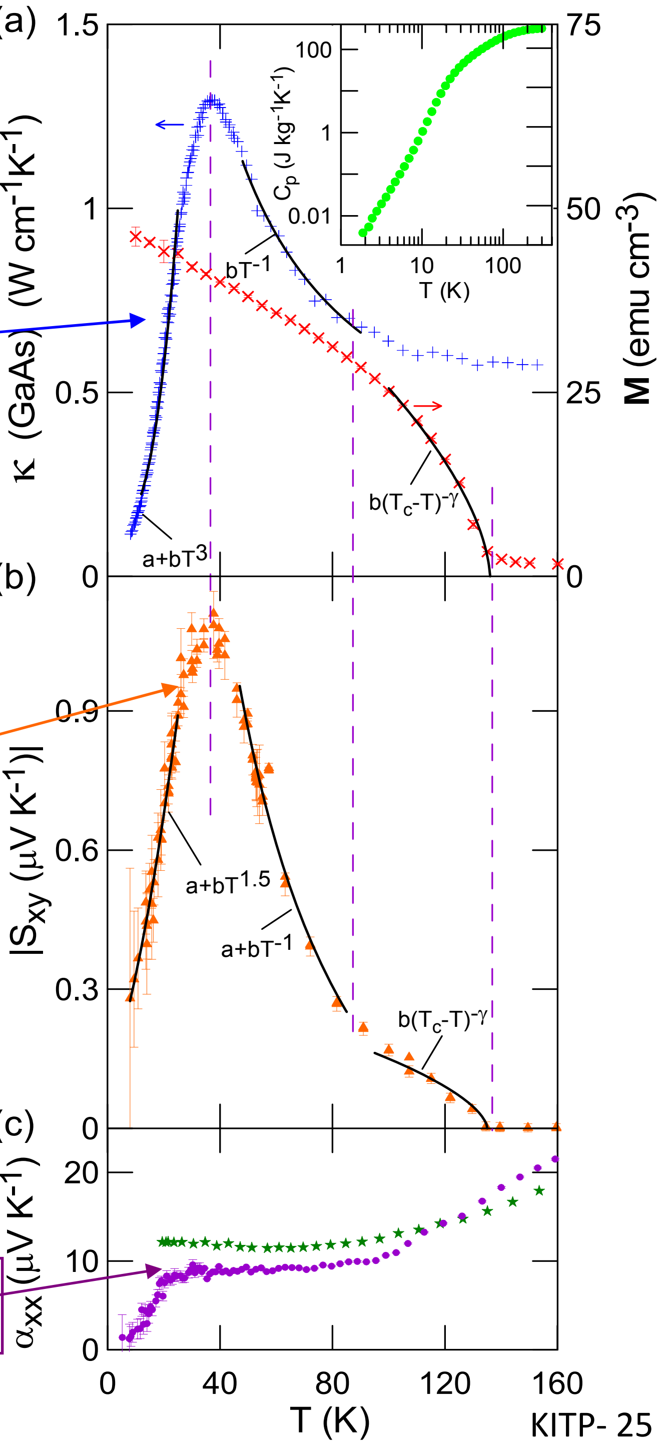
Big

Small

Phonon - Drag Thermo- power

Big

Small

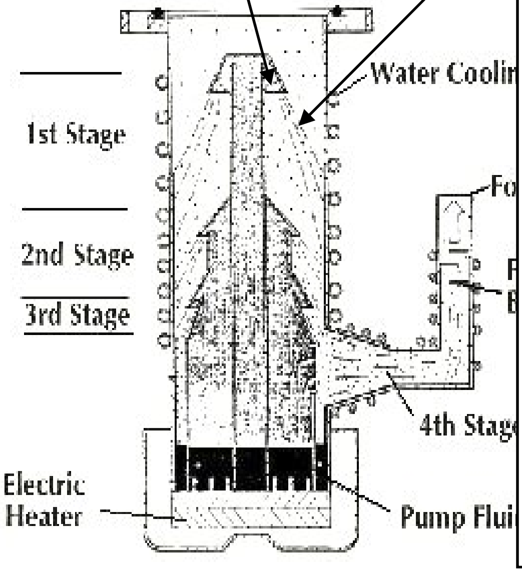


Phonon Drag

A = oil droplets
B = air molecules

A – wall collisions dominate

A – B collisions dominate



When:

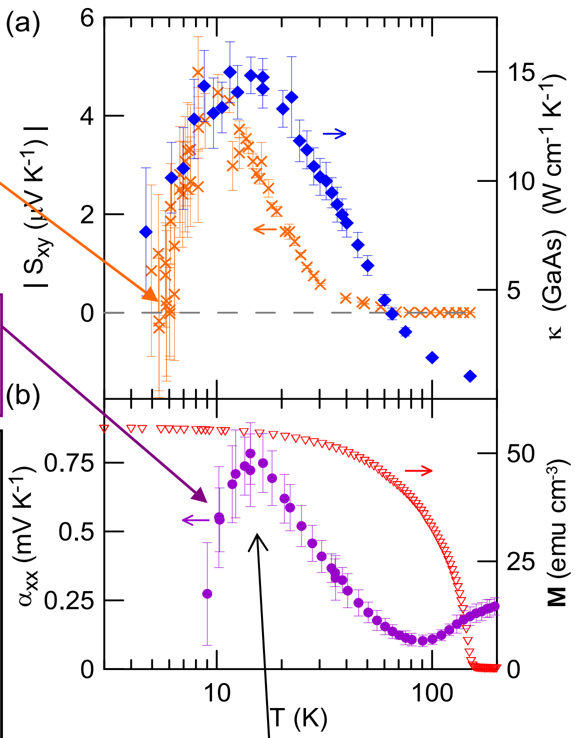
1. A-B collisions dominate both A-scattering and B-scattering
2. A-particles have drift velocity

Then:

1. A-particles impel B-particles with momentum IN ONE DIRECTION
2. Out-of-thermal equilibrium
3. Very intense

A = phonons,
B = magnons

A = phonons
B = electrons



?

How do “phonon-drag” curves get to have a maximum in temperature?

3. InSb

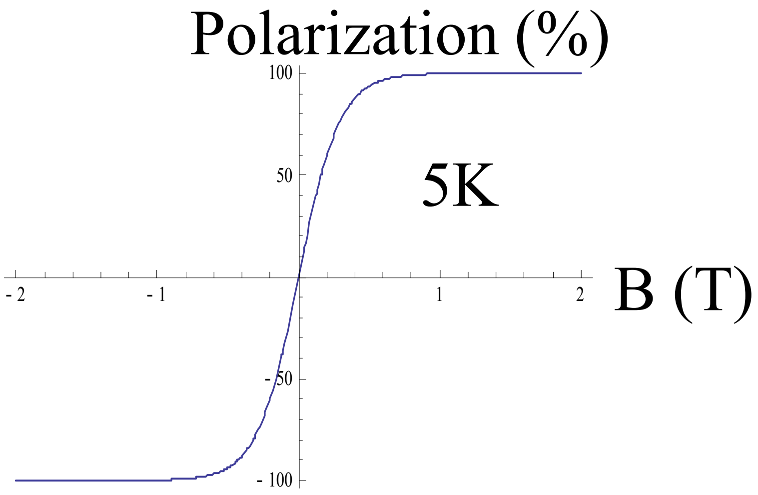
- No exchange coupling: spin polarization from Landau levels
- No magnon conductivity: phonon drag
- Giant spin-Seebeck-like effect

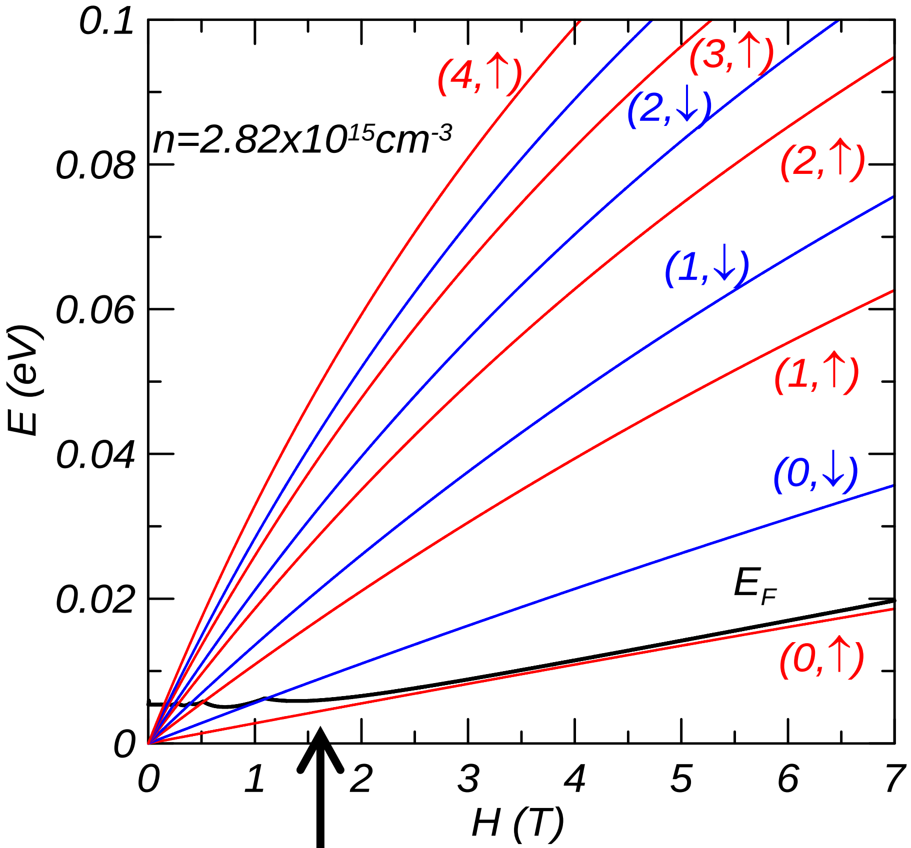
InSb and its Landau levels

Landau level Orbital and Zeeman splitting

$$E \approx \gamma(E) = \frac{\hbar^2 k_x^2}{2m_c^*} + \left(n+\frac{1}{2}\right)\hbar\omega_C + 2sg^*\mu_B H_x$$

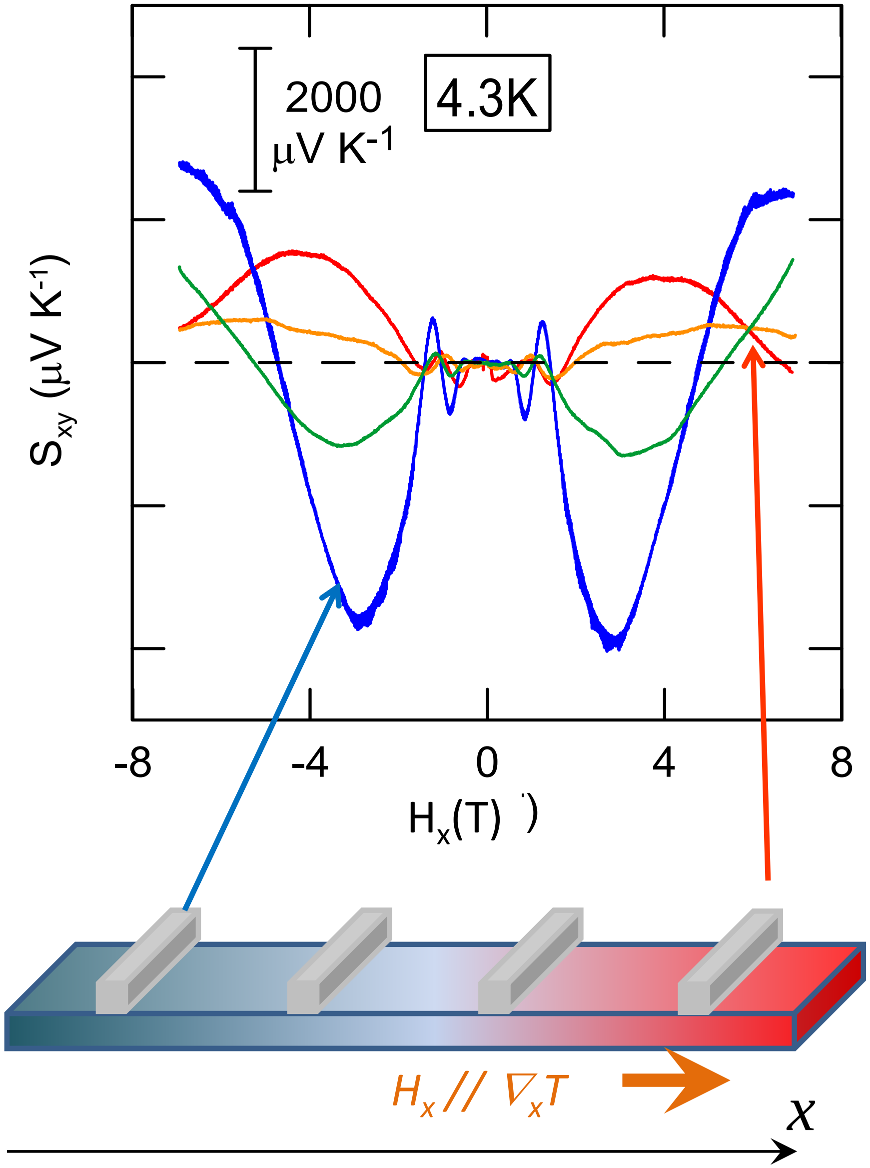
$$\omega_c = \frac{e\hbar H_x}{m_c^*} = \frac{e\hbar H_x}{m^*}$$





From this field on up, most electrons are on the last Landau level (ultra-quantum limit), spin-polarized by Zeeman splitting

InSb Spin-Seebeck data

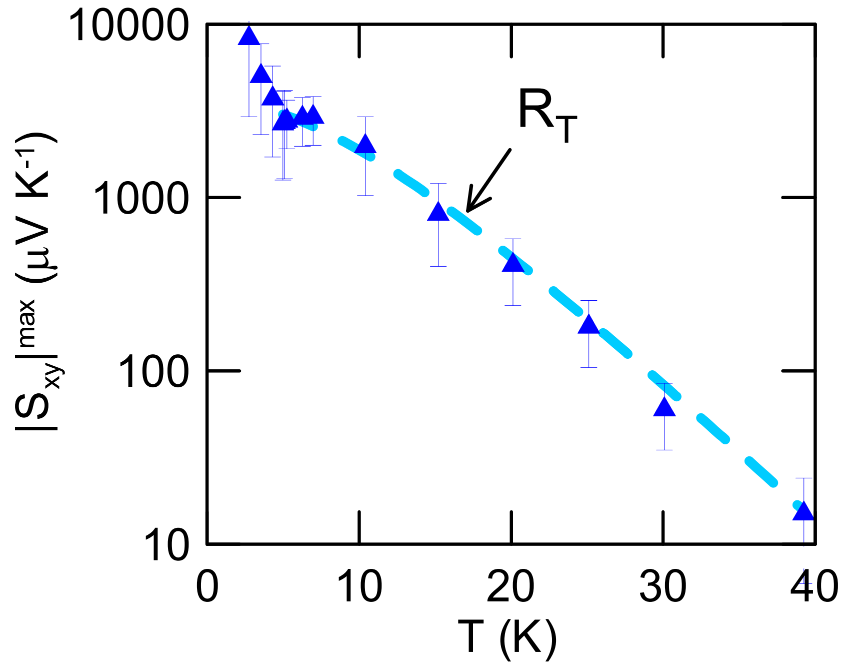


1. Signal is very large, ~8 mV/K
2. Even-symmetric (mostly) as function of magnetic field
3. Even-in-field part:
    1. large
    2. ultra-quantum-field region

Jaworski et al., Nature ***487*** *213 (2012)*

Temperature-dependence of amplitude signature of Zeeman splitting

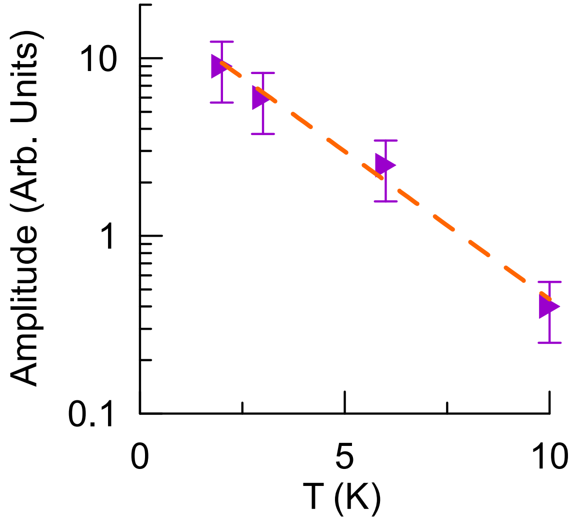
$$\boxed{R_T = \frac{\dfrac{2\pi^2 k_B T}{g\mu_B B}}{\sinh\left(\dfrac{2\pi^2 k_B T}{g\mu_B B}\right)}}$$



Ratio between thermal energy (*k_BT)* and Zeeman energy (*$g\mu_BB$)* for electrons on helical orbits

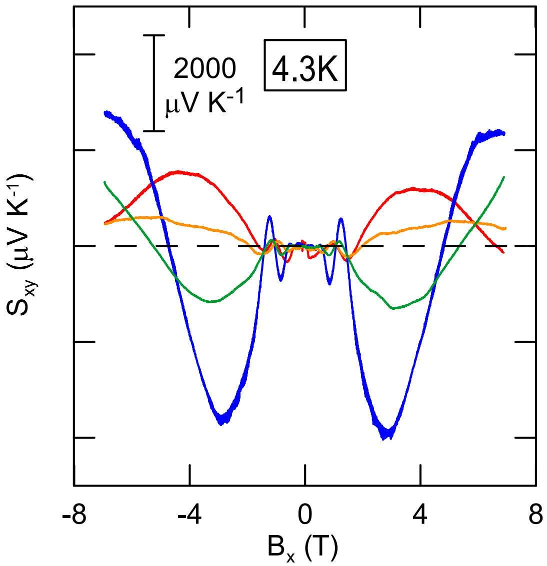
Only adjustable parameter = amplitude

- *R_T* decays slower than SdH oscillations in resistivity
- Spin-Seebeck effect exists even when orbital quantization is no longer resolved



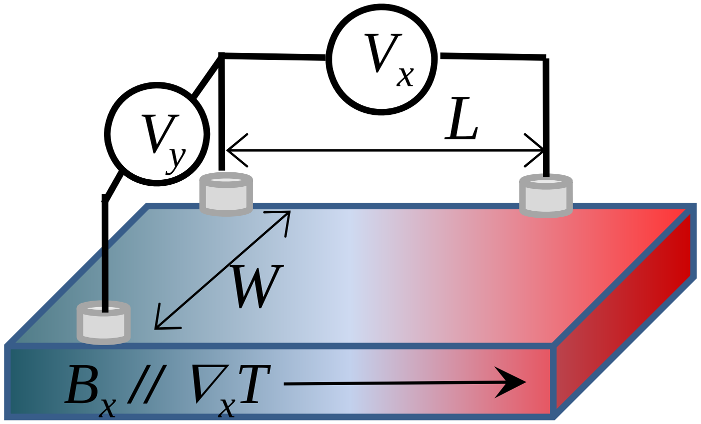
Shoenberg D. Magnetic Oscillations in Metals, Cambridge 1984

Potential Parasitic Voltages

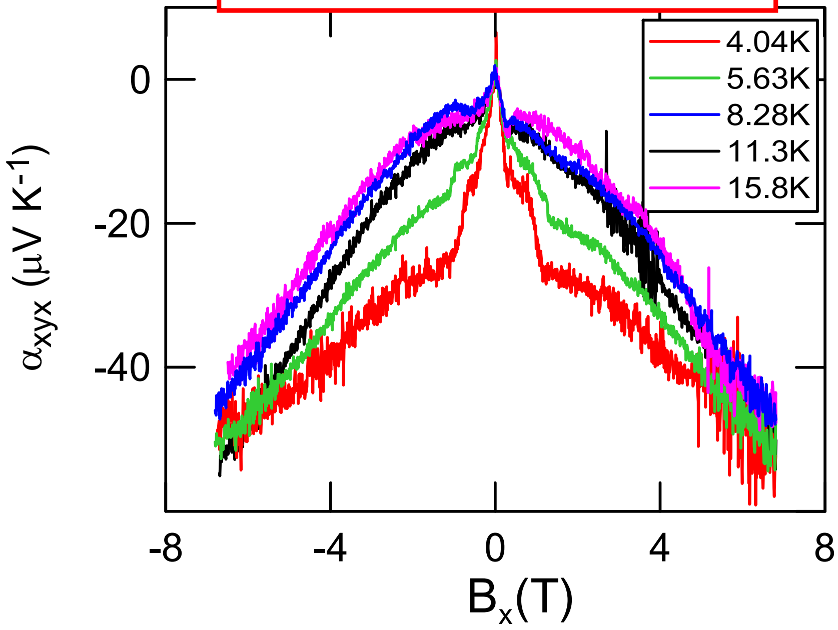


$$\alpha_{xxx} \equiv \frac{V_x / L}{\nabla_x T}(B_x)$$

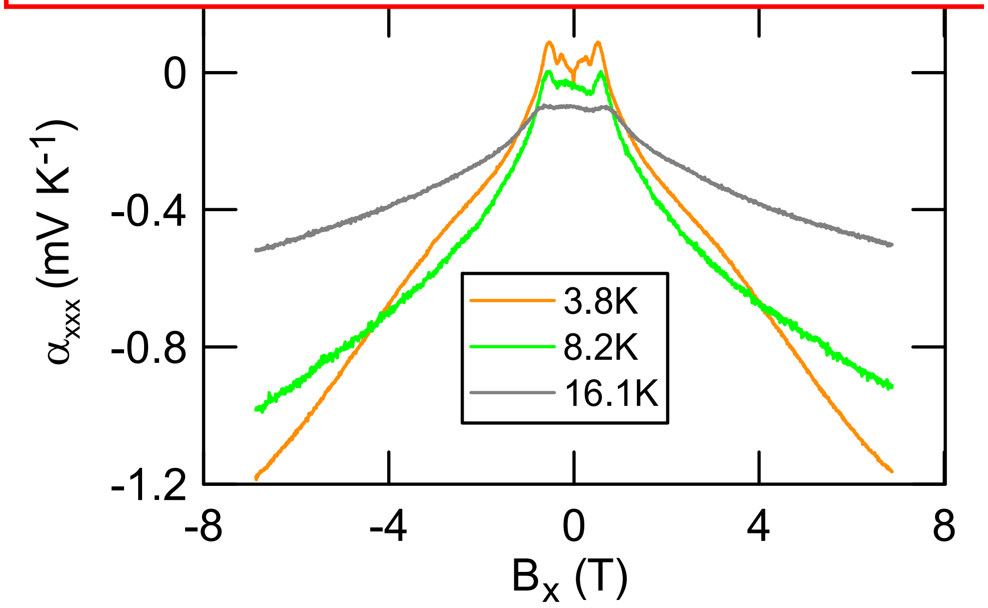
$$\alpha_{xyx} \equiv \frac{V_y / W}{\nabla_x T}(B_x)$$



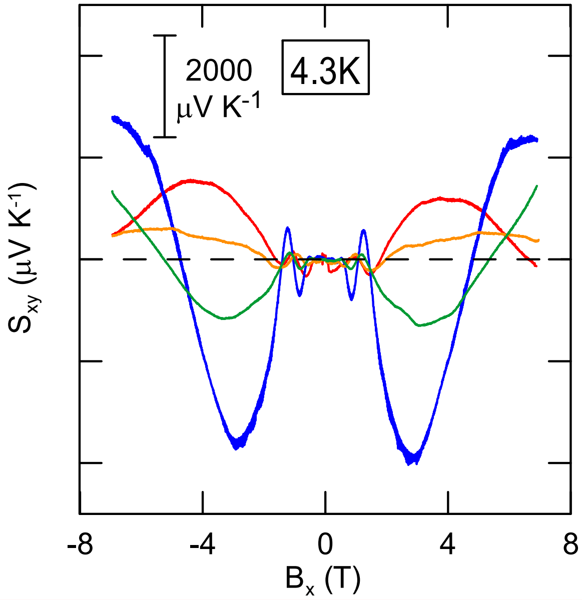
SSE configuration

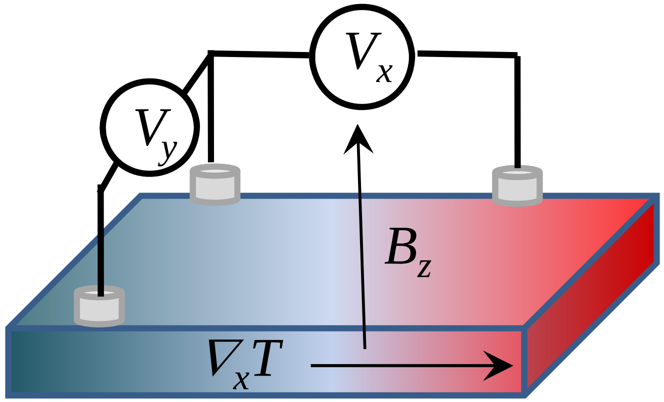


Longitudinal magnetothermopowe



Potential Parasitic Voltages



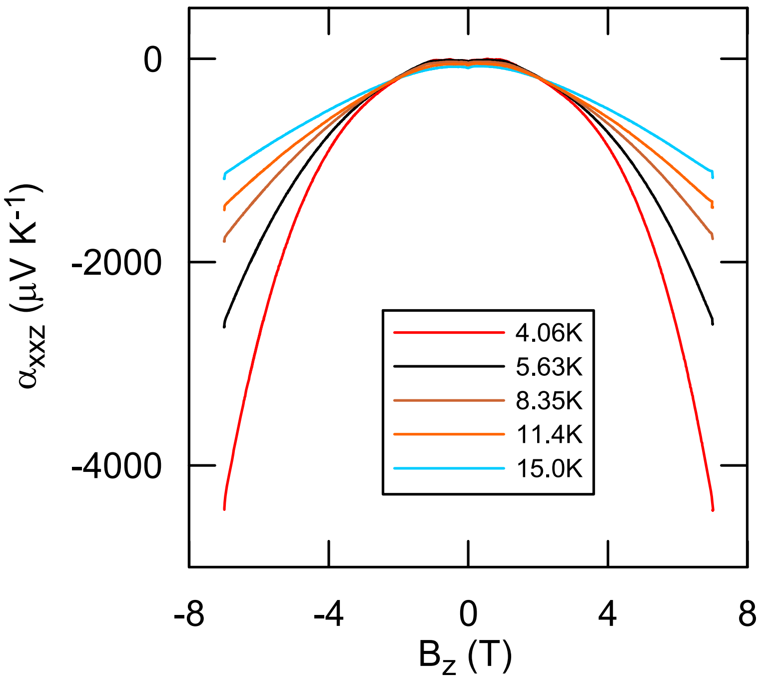


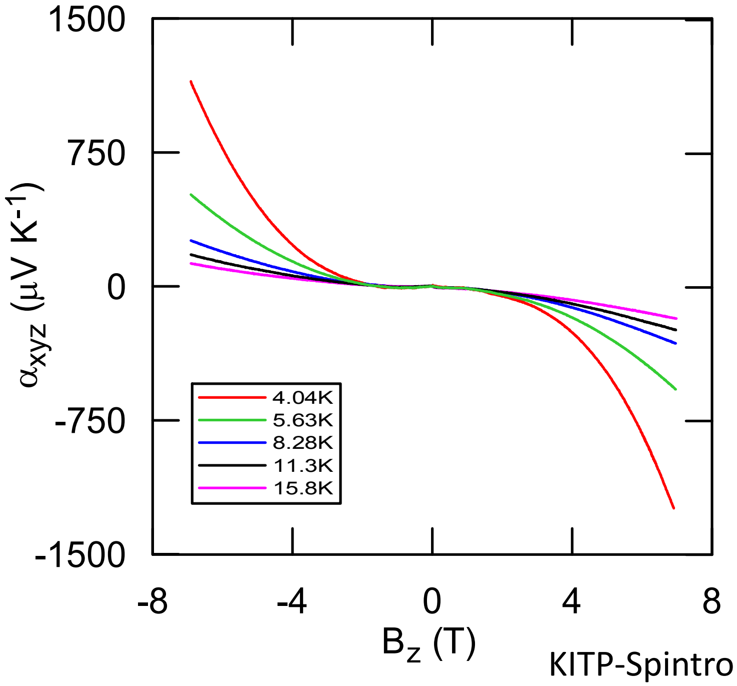
$$\alpha_{xxz} \equiv \frac{V_x / L}{\nabla_x T}(B_z)$$

$$\alpha_{xyz} \equiv \frac{V_y / W}{\nabla_x T}(B_z)$$

Transverse magnetothermopowe

Conventional Nernst effect





The physics:

1. Temperature gradient creates phonon flux

Change in phonon momenta: $$\Delta q \equiv {k_B \Delta T}/{\hbar c}$$

2. Strong phonon-drag impels additional momentum $\Delta \mathbf{k}$ to electrons: $$\Delta k_x = \Delta q$$

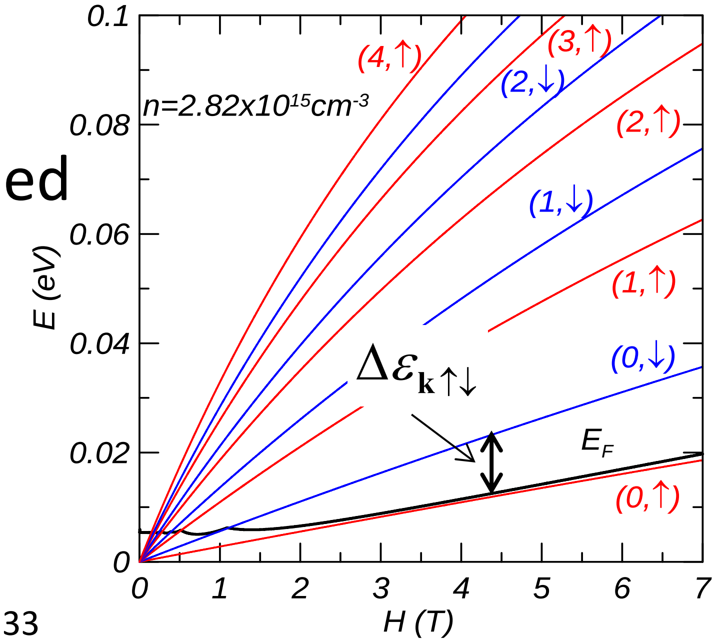
3. Strong spin-orbit interactions transform $\Delta \mathbf{k}$ into a change in Zeeman splitting energy: $$\Delta \varepsilon_{\mathbf{k}\uparrow\downarrow} = \beta \Delta k_x$$

We actually can estimate β from published concentration-dependence of *g*-factor

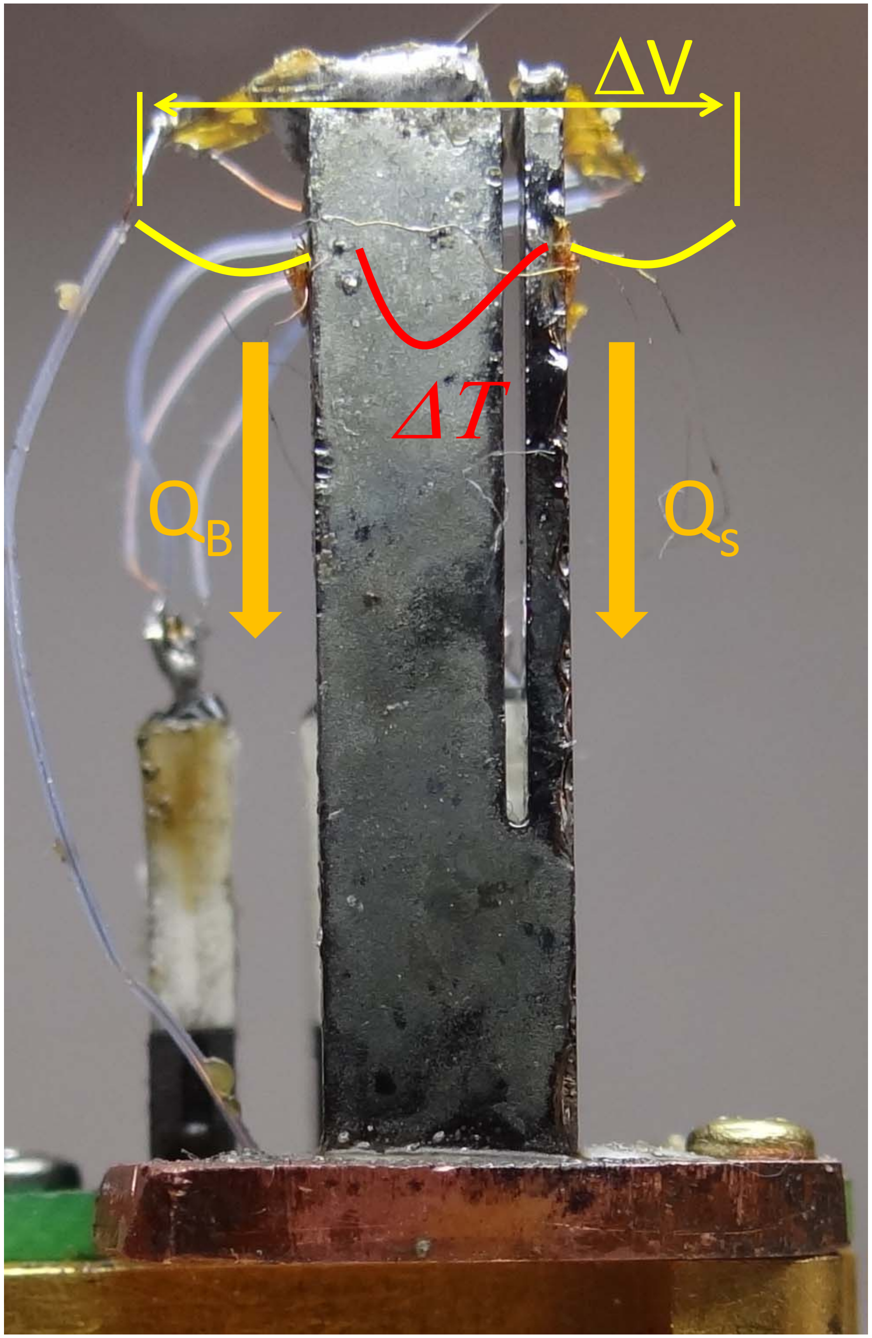
$\Rightarrow$ no adjustable parameters,

$\Rightarrow$ for *T=5K, ΔT=40 mK:*

$$\Delta \varepsilon_{\mathbf{k}\uparrow\downarrow} \approx 120 \mu eV \approx 25\% \text{ of } k_B T$$



Phonon-drag: the length scale = ½ cm

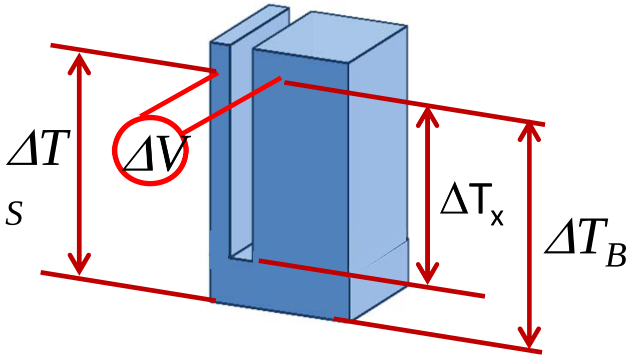


$$\alpha_{PED} = \frac{C_V}{3ne} R$$

$$R = \frac{\tau_{PED}^{-1}}{\tau_{PED}^{-1} + \tau_{\varphi}^{-1}}$$

Narrow arm: τ_φ short R_S small

Wide arm: τ_φ long R_B large

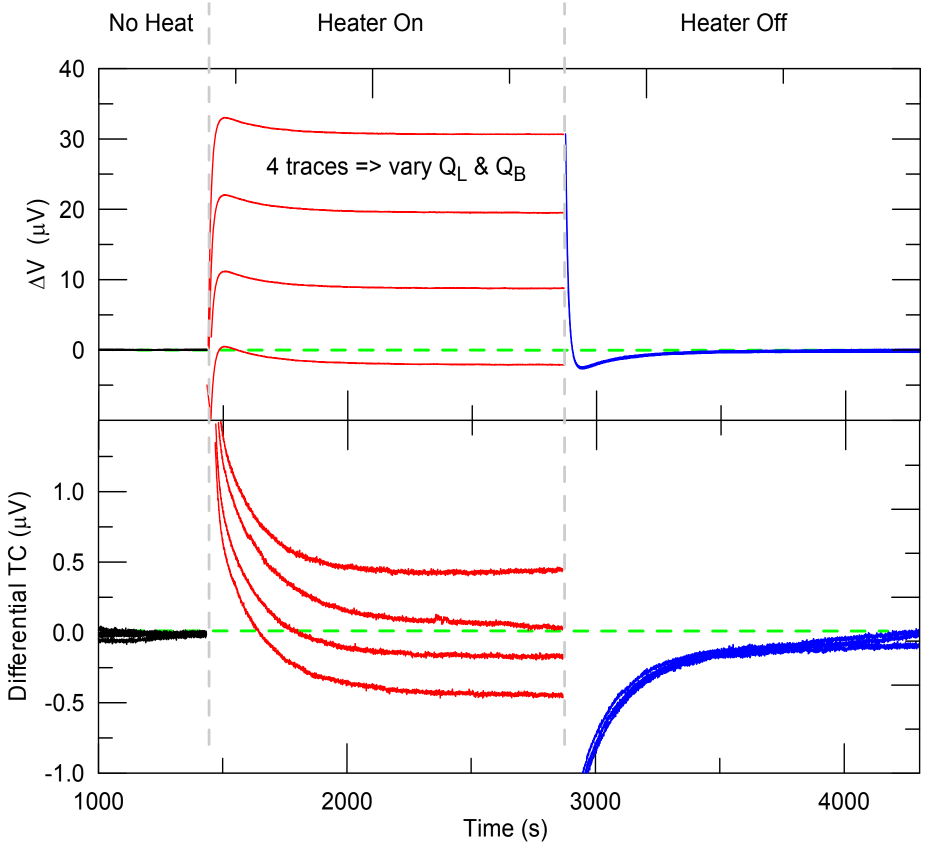


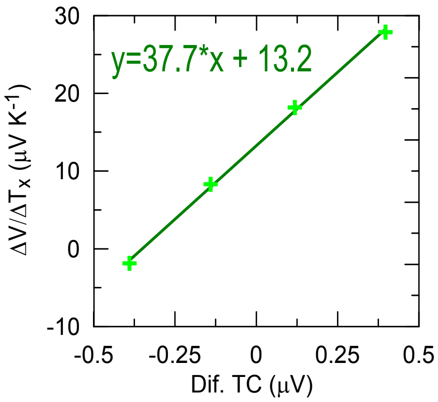
$$\Delta\alpha \equiv \left.\frac{\Delta V}{\Delta T}\right|_{\Delta T_S = \Delta T_B} = \frac{C_V}{3ne}\left(R_B - R_S\right)$$

Electrons and diffusion thermopower cancel out

Jin & al, unpublished

Principle of measurement: thermal potentiometer



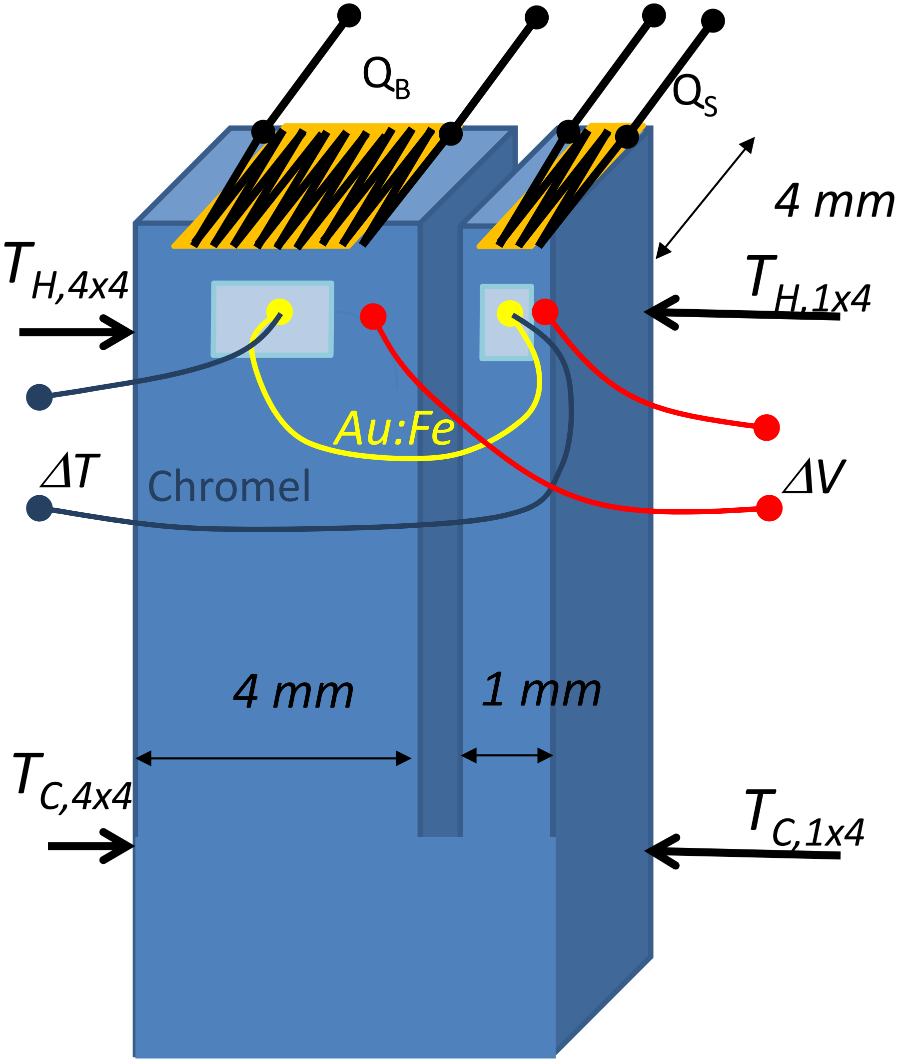


When ΔT = 0

$$\frac{Q_B}{Q_S}=\frac{1}{4}\frac{\kappa_B}{\kappa_S}$$

$$\Delta\alpha \equiv \left.\frac{\Delta V}{\Delta T}\right|_{\Delta T_S=\Delta T_B}$$

$$=\frac{C_V}{3ne}\left(R_B-R_S\right)$$



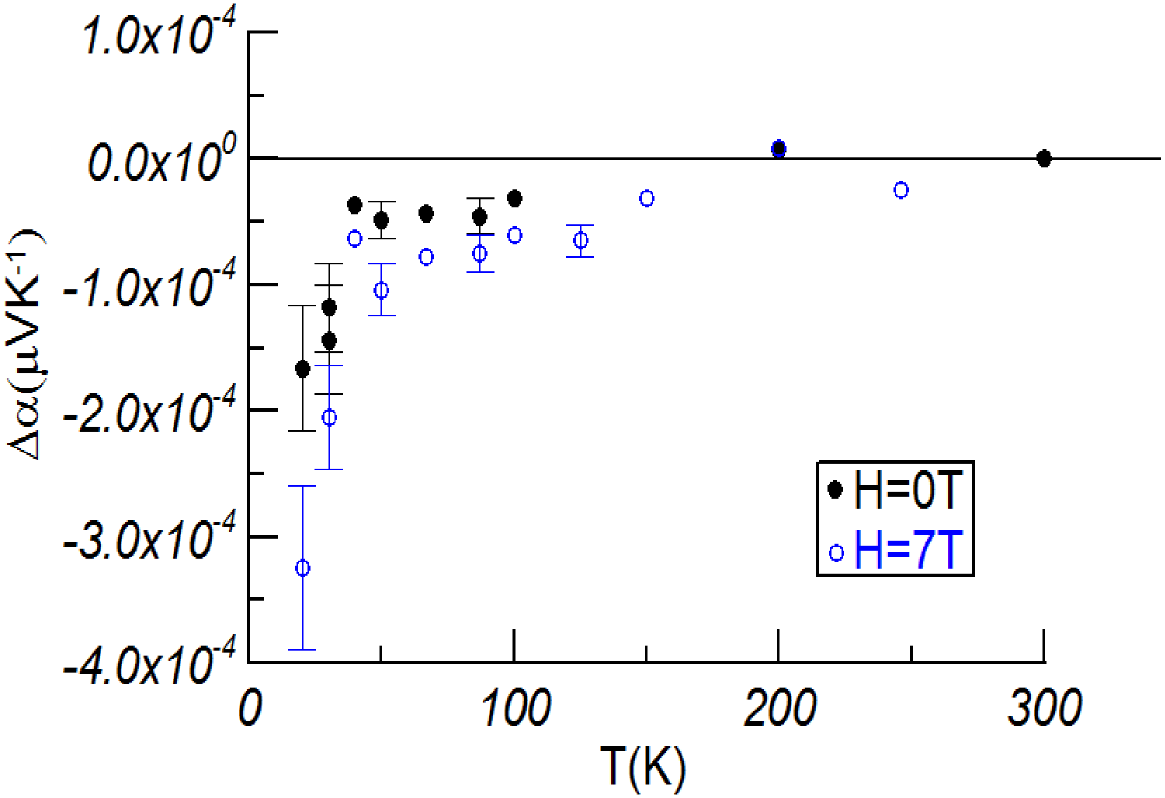
Differential thermal thermopower purely due to phonon drag

Pure phonon thermopower

Length scale > 0.4 cm

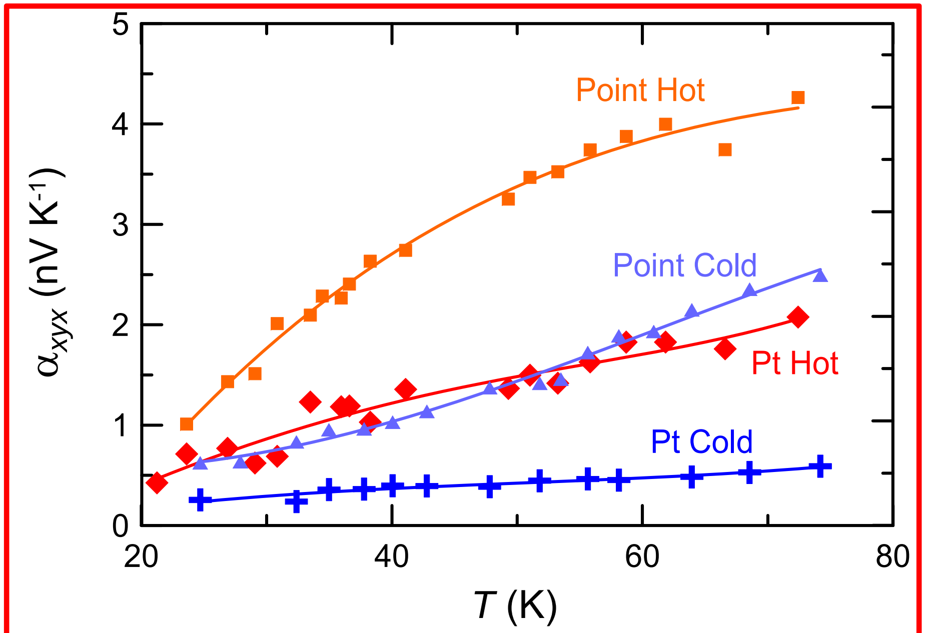
$$\Delta\alpha \equiv \left.\frac{\Delta V}{\Delta T}\right|_{\Delta T_S = \Delta T_B}$$

$$= \frac{C_V}{3ne}\left(R_B - R_S\right)$$

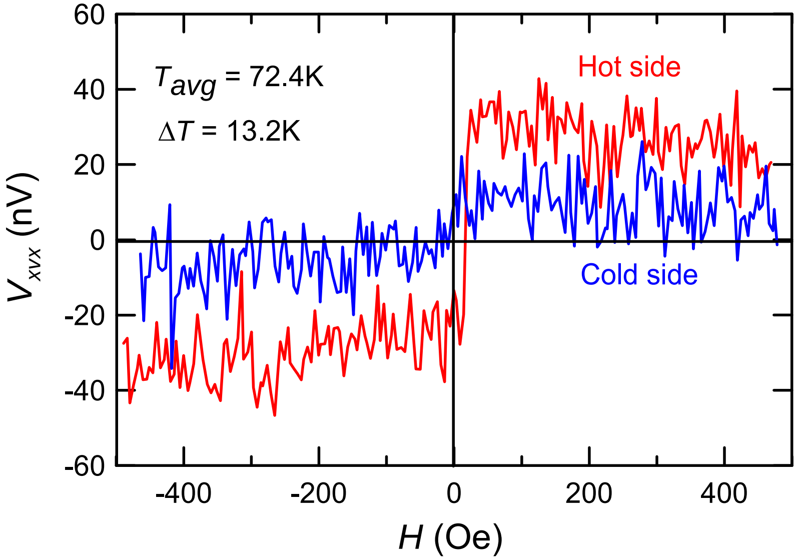


Jin & al, unpublished

4. SSE signals on Metglass



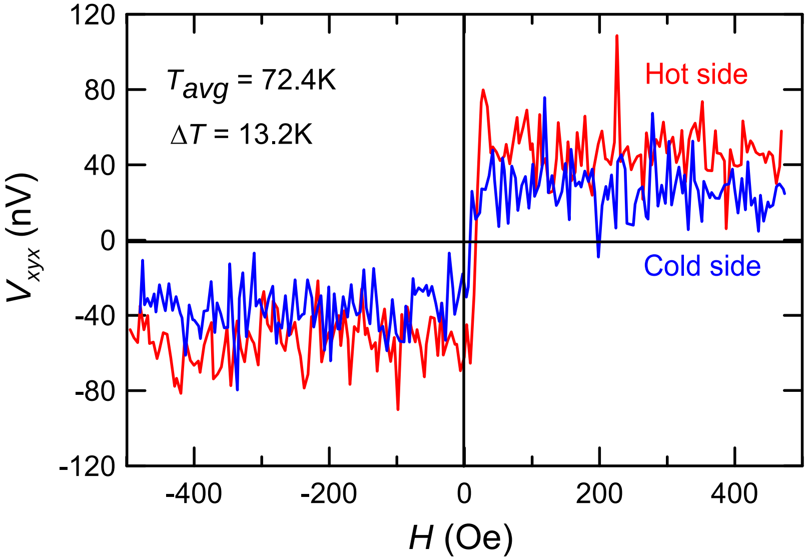
Cu + Pt



- $Co_{80}Si_5BFeMoNi$: Ferromagnetic BULK metallic glass (Metglas)
- High T_c, yet mostly localized phonon modes (Einstein modes)
- No phonon drag contribution
- Sample is bulk => no contamination with ∇_z

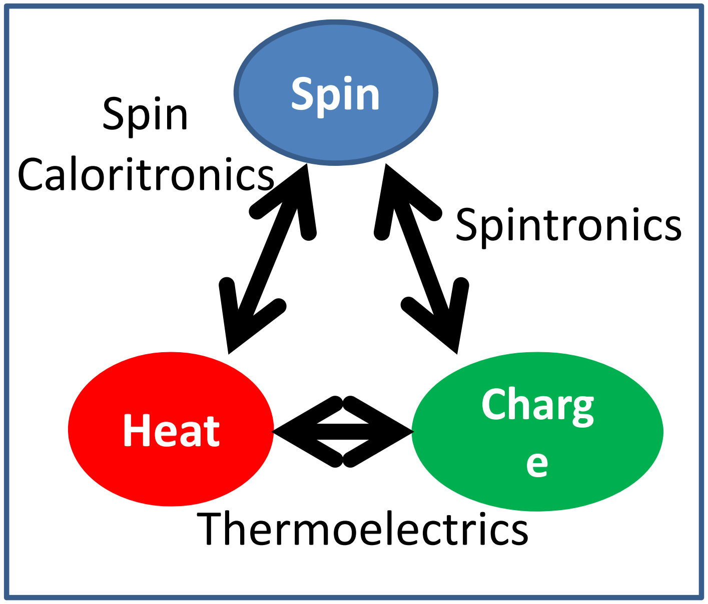
TSSE exceedingly small, a few nV/K

Point contact



Jin & al., Solid State Commun. (subm., 2013)

Conclusions



1. Longitudinal spin-Seebeck effect understood.
2. Transverse spin-Seebeck effect:
   the length scale of the effect is surprising
1. Two mechanisms put spin-waves out of thermal equilibrium:
   1. Magnon thermal conductivity
   2. Phonon drag
2. Mechanisms, Length scales, and Magnitude of TSSE:

Material	Mechanism	Mean free path	Magnitude of TSSE signal
InSb	Phonons	Sample size, 0.5 cm (<40K)	8 mV/K (4K)
GaMnAs	Phonons Magnons	In GaAs substrate similar to InSb ?	5 μV/K (10K) < 1 μV/K (80K)
YIG	Phonons Magnons	Sample size (2K); 5 μm (20K) 50 μm (2K); 5 μm (20K)	LSSE only ~ 0.5 to 1 μV/K (300K) ~ 10 μV/K (50K)
Metglas	Phonons Magnons	< nm ?	3 nV/K