Magnon, Spinon and Phonon in spin caloritronics

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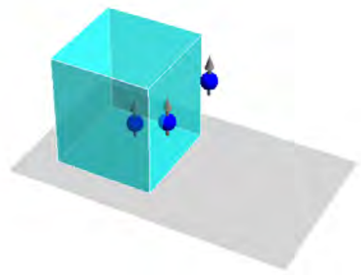
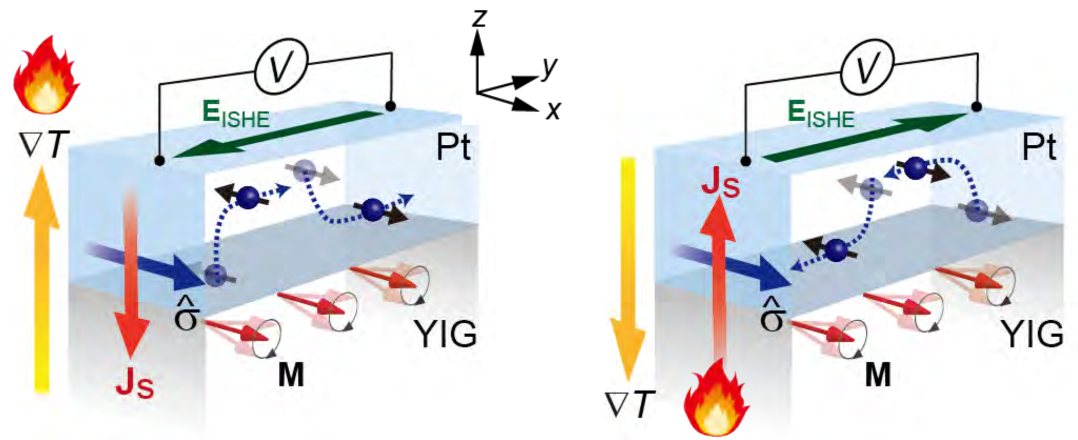
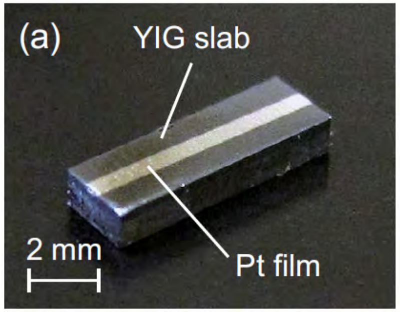


Contents

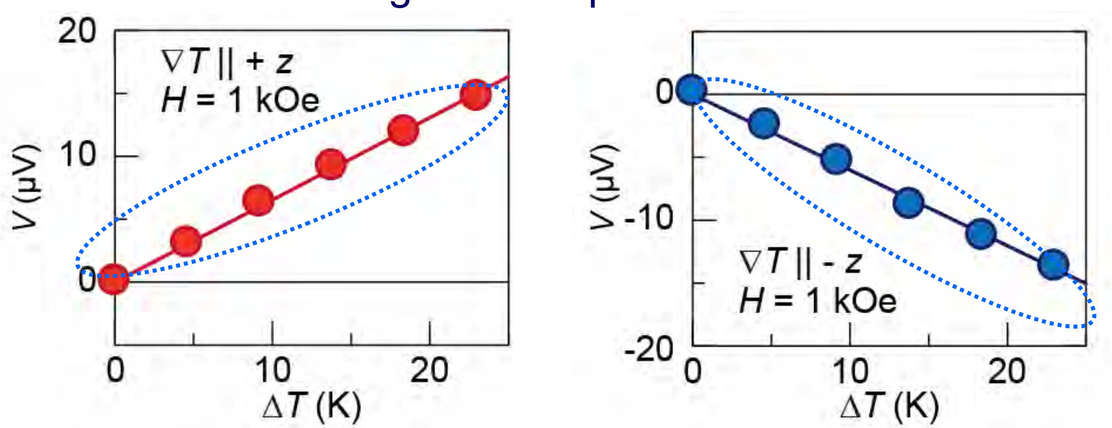
Spin Seebeck effect
= thermal SP



sample:
Pt(15 nm)/YIG slab



Voltage vs Temperature difference

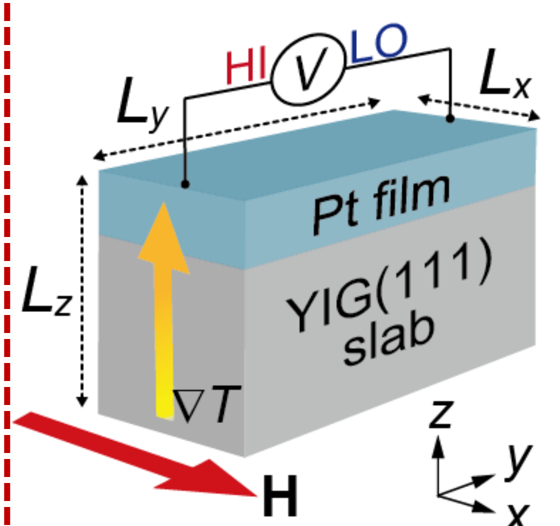


Voltage vs Magnetic field

Nature **445**(2004)778 , APL **97**, 172505 (2010)

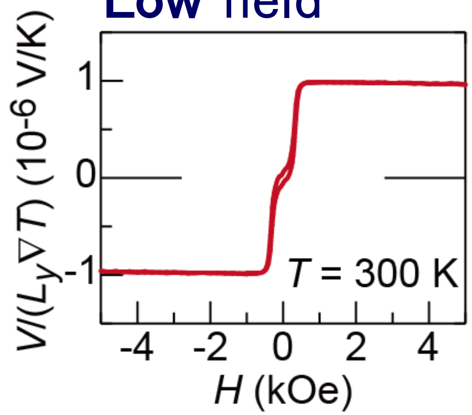
Spin Seebeck effect (in Bulk)

Pt(5 nm)/bulk YIG

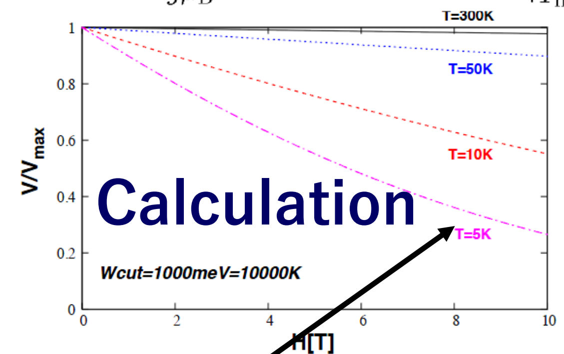


(L_x, L_y, L_z)
= (2 mm, 4 mm, 1 mm)

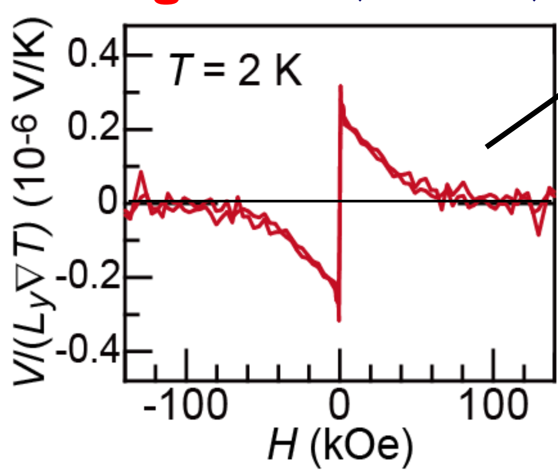
Low field

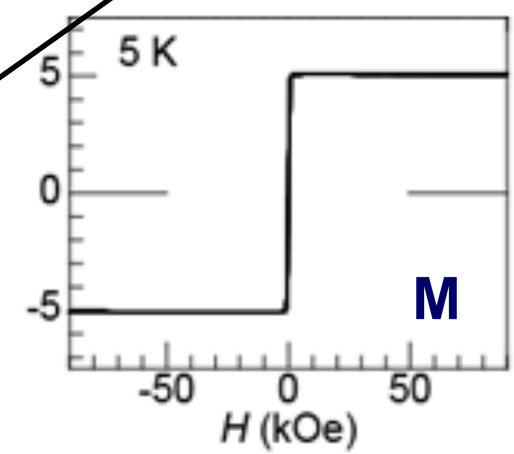


$$V_{\mathrm{LSSE}}(H,T) \propto \int_{g\mu_{\mathrm{B}}H}^{\infty} d\epsilon\, D(\epsilon,H)\epsilon \frac{\partial f_{\mathrm{BE}}}{\partial T_{\mathrm{m}}}\bigg|_{T_{\mathrm{m}}=T}$$



High field (in Bulk)





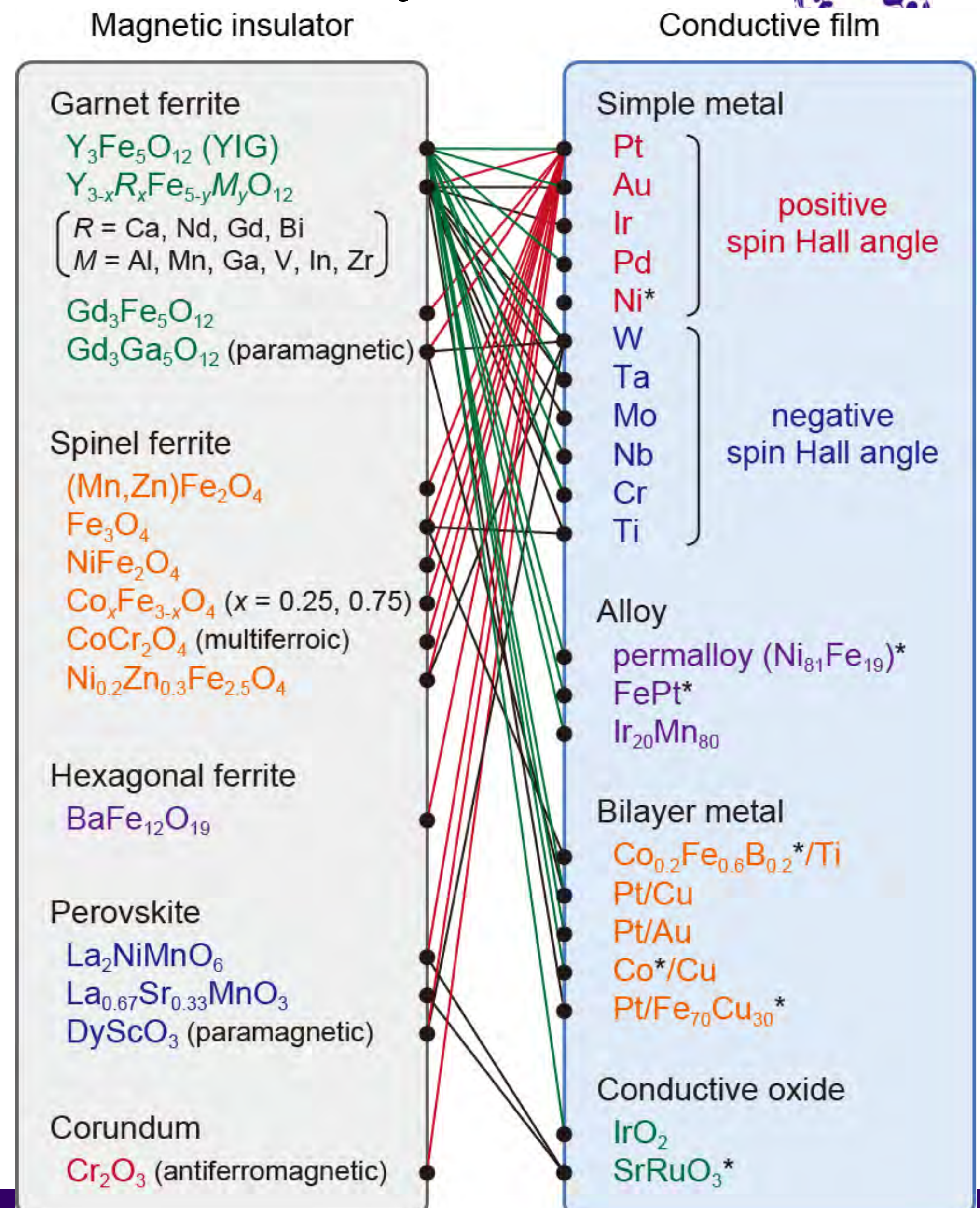
SSE has been reported in a lot of systems

SSE is a universal phenomenon in magnetic materials

Model system:

Pt/$Y_3Fe_5O_{12}$ (YIG) junction

K. Uchida, H. Adahci, T. Kikkawa, A. Kirihara, M. Ishida, S. Yorozu, S. Maekawa, and E. Saitoh, “Thermoelectric generation based on spin Seebeck effects” Proceedings of the IEEE (2016), DOI:10.1109/JPROC.2016.2535167.



development of SSE efficiency since its discovery

TOHOKU UNIVERSITY

~ 400 times greater

today's world record @ R.T. (Zaragoza group)

	σ (1/Ω cm)	κ (W/cm K)	S (μV/K)	P.F.(μW/cm K^2)	ZT
12x[Pt(5nm)/Fe_3O_4]/ MgO substrate	260000	0.60	5.4	7.5	0.0038
1x[Pt(5nm)/Fe_3O_4]/ MgO substrate	28000	0.60	1.1	0.032	0.000016
Pt/$Y_3Fe_5O_{12}$ (2013)	46500	0.074	1.3	0.073	0.00030
Pt/$Y_3Fe_5O_{12}$ (2010)	46500	0.074	0.23	0.0024	0.000010

$\Delta V \equiv$ peak-to-peak voltage

$S_{SSE} \equiv (\Delta V/\Delta T)(L_z/L_y)$ (μV/K)

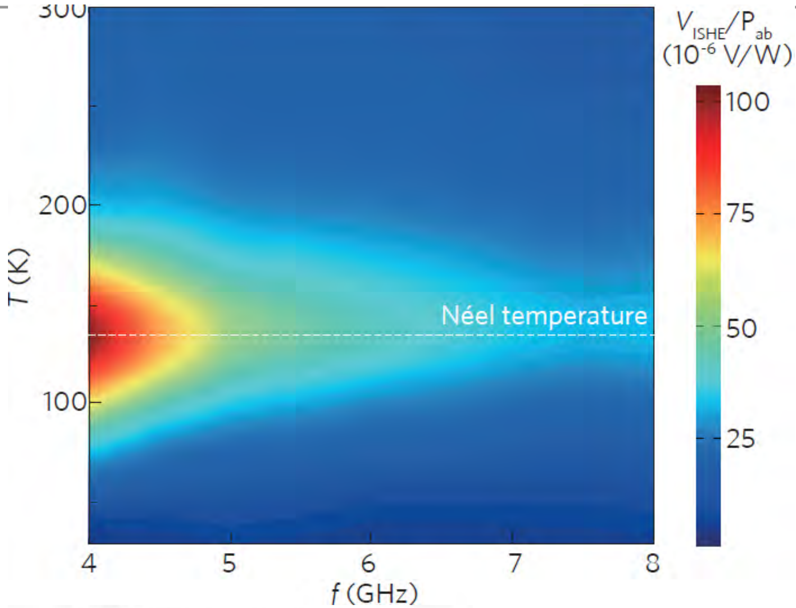
$\sigma_{eff} \equiv (R \times (L_x\, t_{top\ Pt}) / L_y)^{-1}$ (1/Ω cm)

P. F. $\equiv \sigma_{eff}\ S_{SSE}^2$ (μW/K^{2}cm)

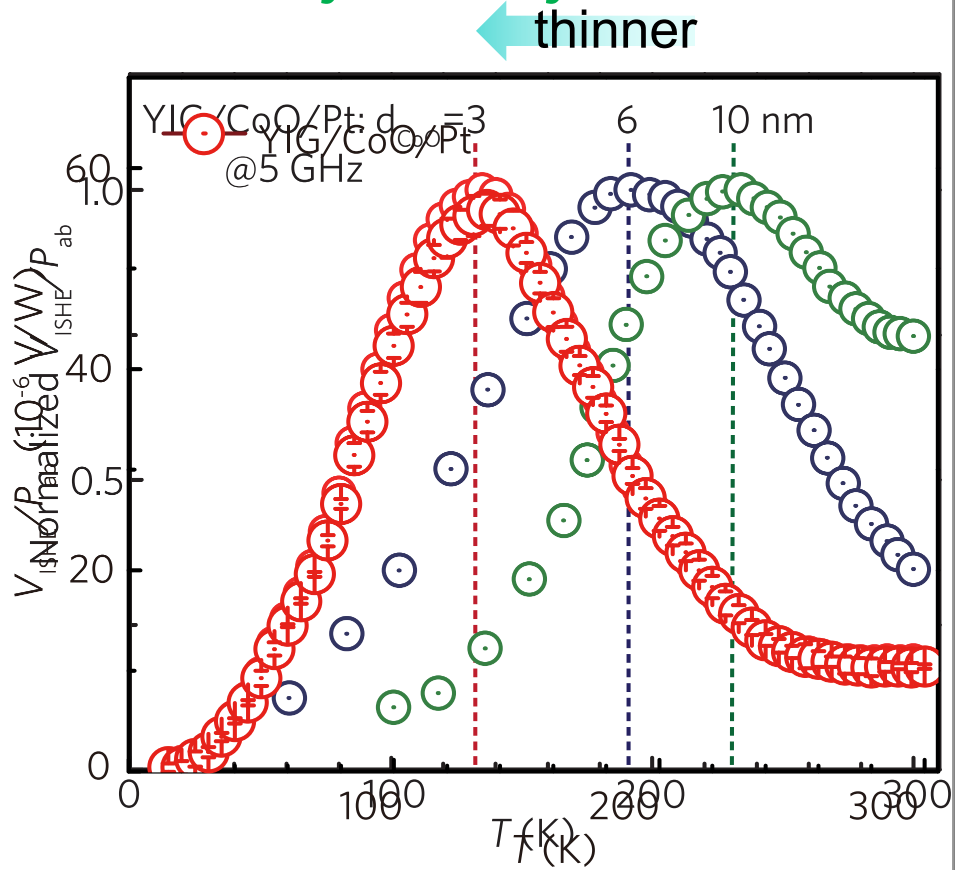
our first observation of SSE

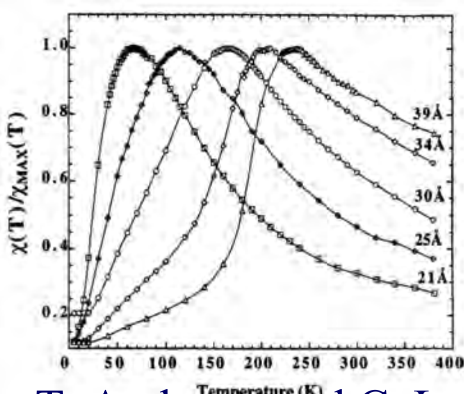
cf. ZT (n-type Si)~0.005

SP can be used to magnetometry for very thin films



SP allows us to measure magnetic properties electrically ***even in very small systems***



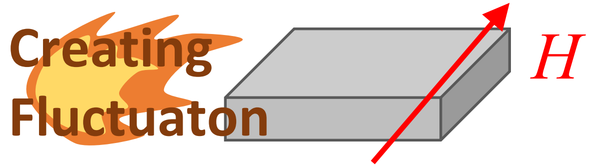


Cf.

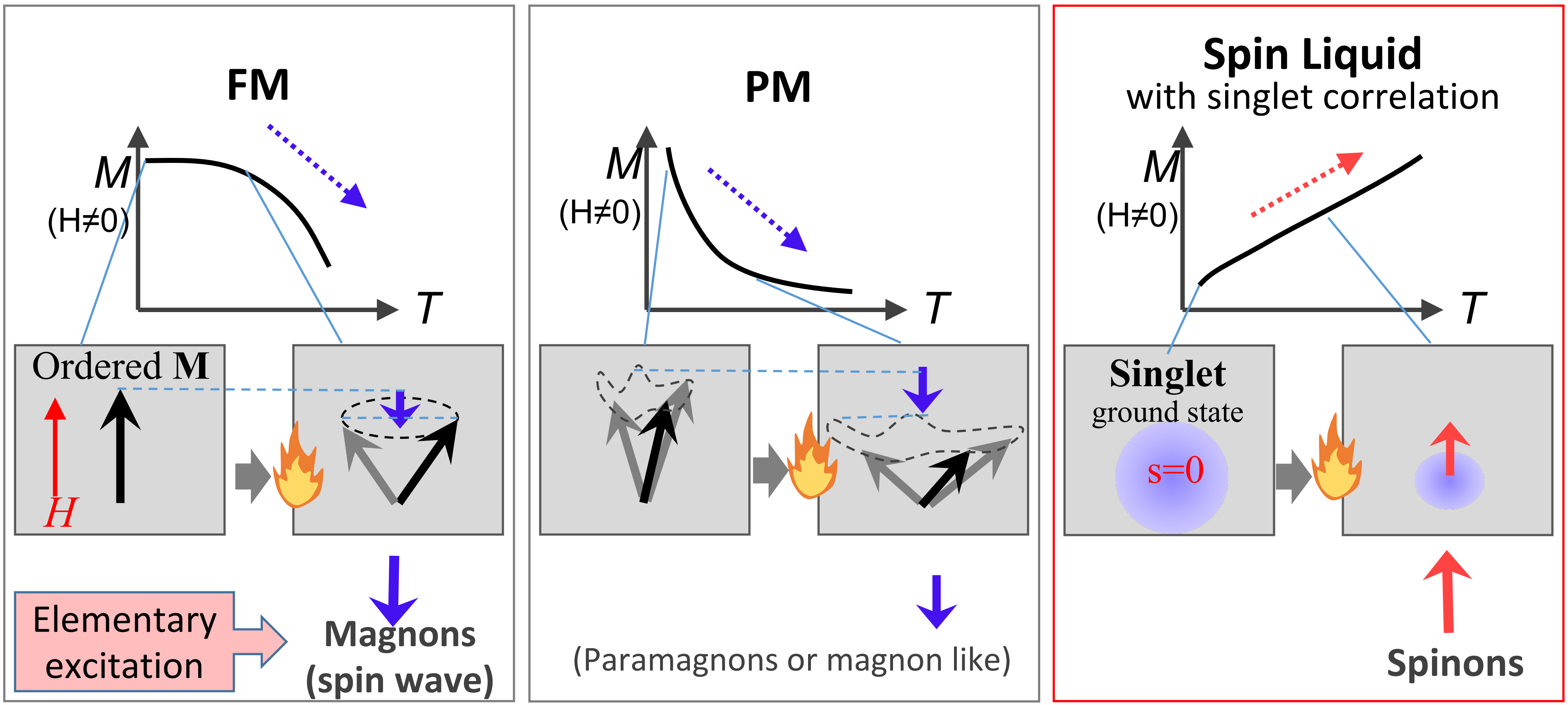
χ for CoO film

T. Ambrose and C. L. Chien PRL**76**,1743

For SSE, fluctuation is created

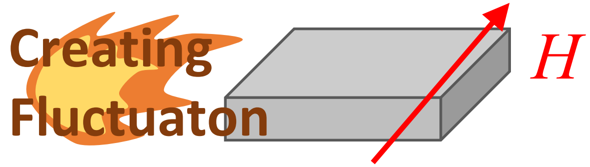


Spinon spin current has Opposite sign

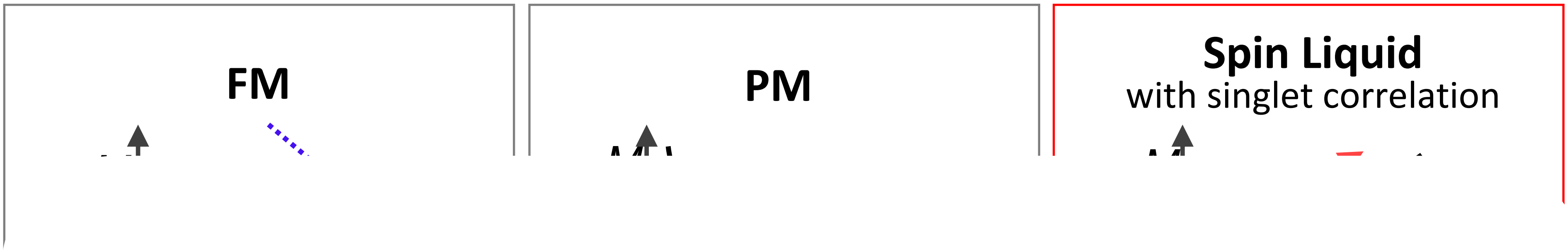


Spinon: excitation from quantum spin liquid

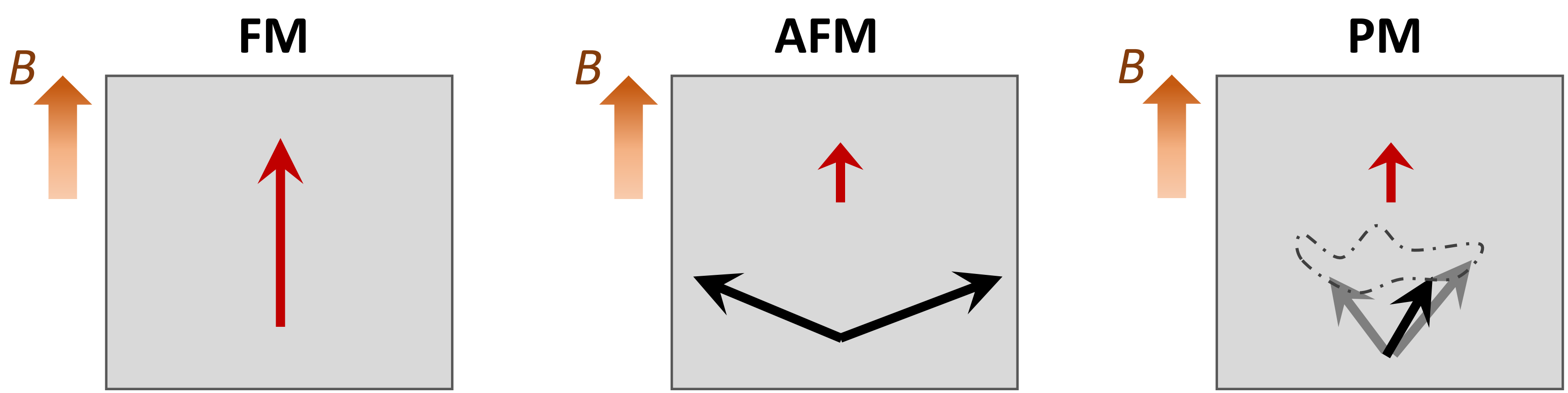
For SSE, fluctuation is created



Spinon spin current has Opposite sign



First, magnetic field is applied to align magnetic moment



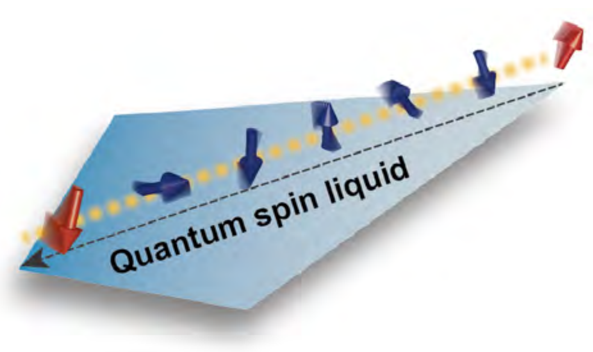
Long range spinon correlation in 1D SC

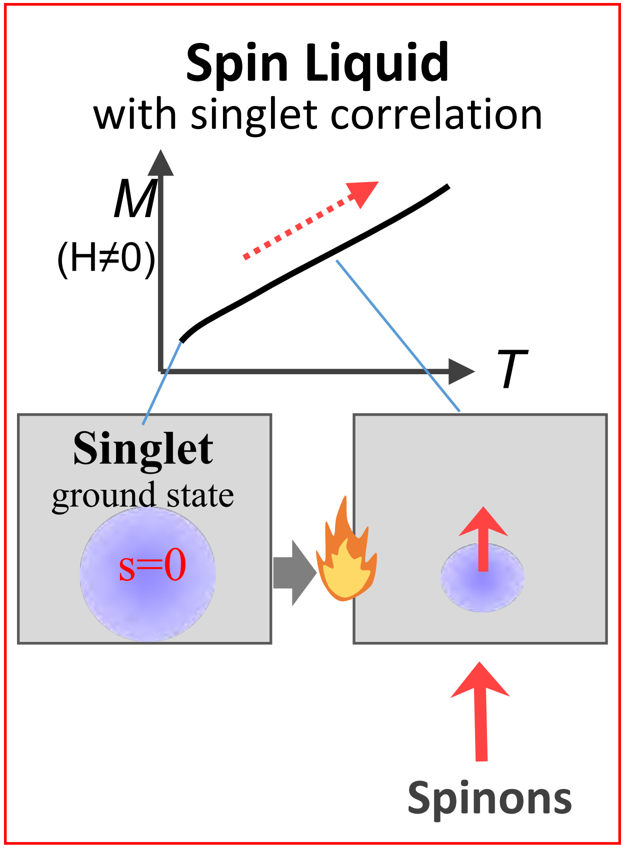
Spinon Spin current in Luttinger liquid in 1D spin chain

Long-range (theoretically, ∞) **spincurrent**

owing to long-range spin correlation
due to ***critical*** quantum fluctuation
(Tomonaga Luttinger)

- *realized in one-dimensional S=1/2 chains*





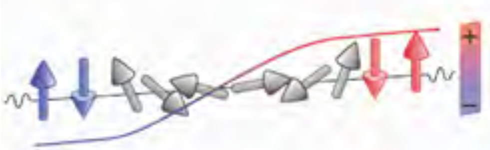
Spinon: excitation
from spin quantum liquid

Spinon excitation in 1D Quantum Spin Liquid (QSL)

1D Spinons：collective excitations in one-dimensional QSL

In spite of *NO* magnetic ordering (Paramagnetic)

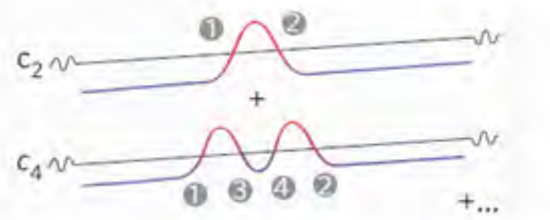
Individual spinon



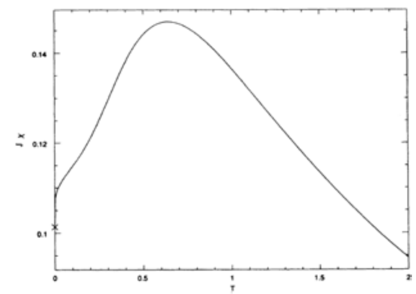
M. Mourigal, et al., Nature Phys. **9**, 435-441 (2013)

'domain-wall-like excitation'

Pair excitations



Magnetic susceptibility

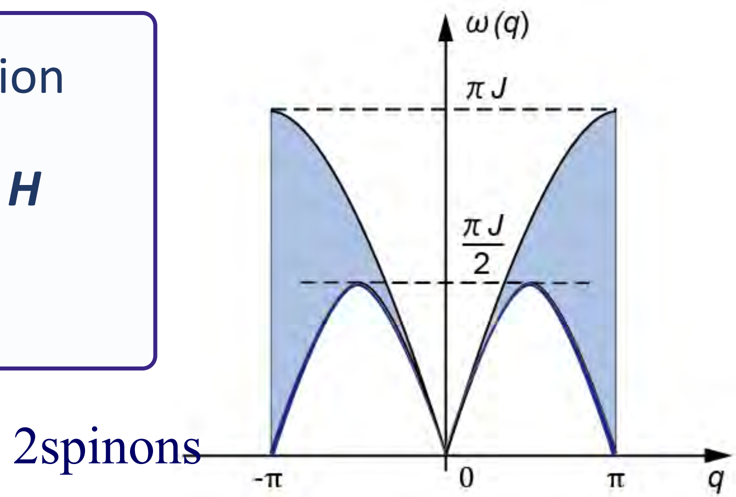


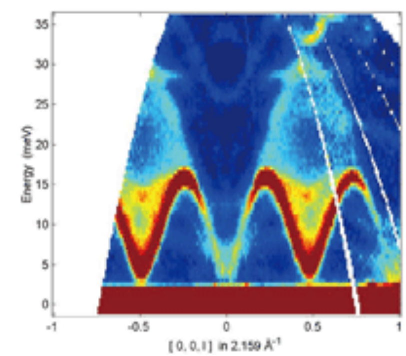
S. Eggert, et al., PRL. **73**, 332-335 (1994)

Gapless excitation

- *S*=1/2 fractional excitation
- Gapless ***robust against H***

Continuous spectrum



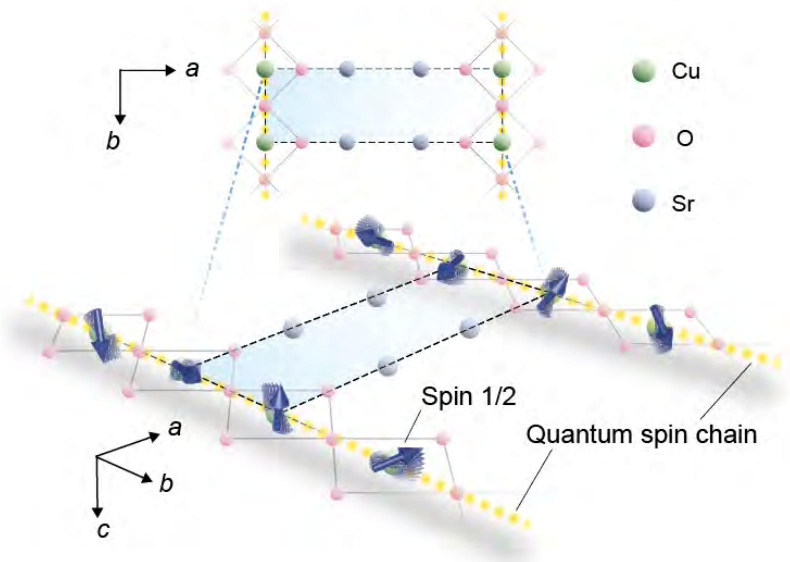


・*gapless spinon robust against magnetic fields*

material in which spinon is well established

Paramagnetic Insulator Sr2CuO3

One-dimensional spin chains

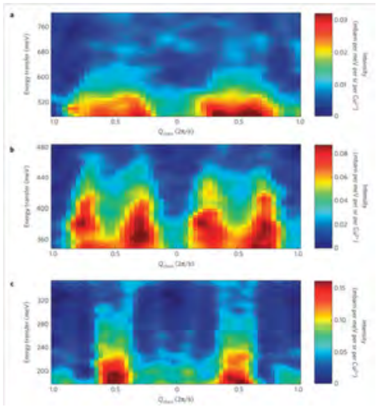


- **Cu-O chains along *b*-axis**
- **Exchange coupling ~2,000 K**

Single crystals grown by a TSFZ method
were used in this study

Neutron scattering

ω vs. k

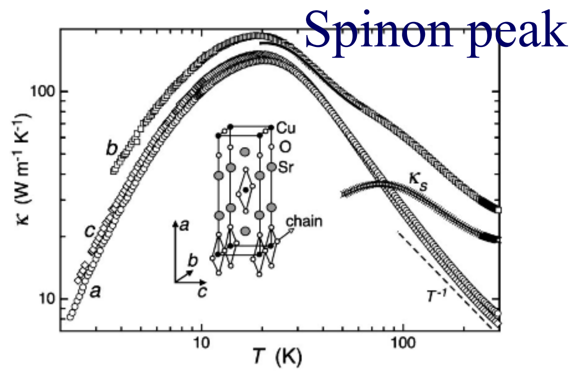


A. C. Walters, et al., Nat. Phys. **5**, 867 (2009)

Continuous spectrum consistent with theory

Thermal conductivity (5N)

κ vs. T



A. V. Sologubenko, et al., PRB **62**, R6108(R) (2000)

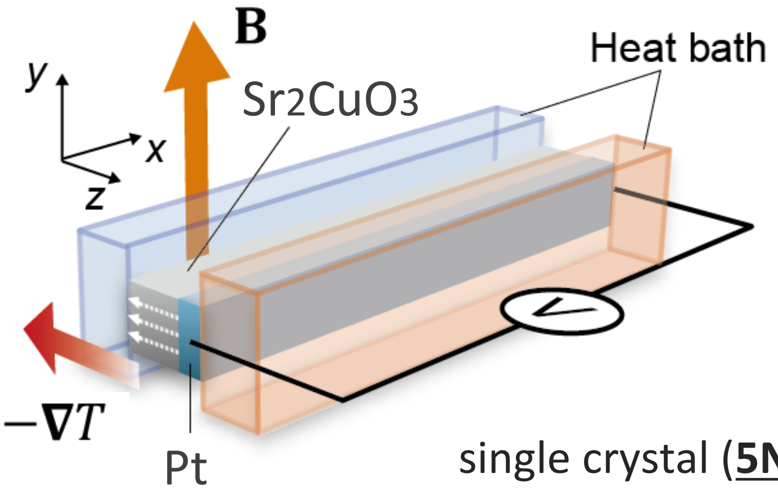
Additional heat conduction along one-dimensional chains

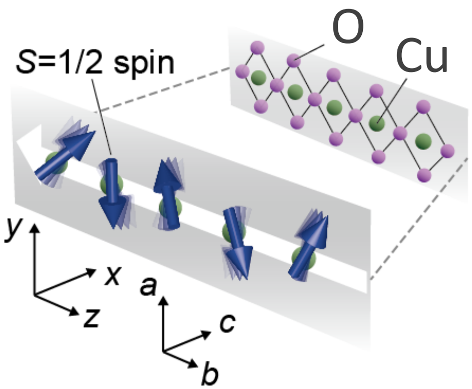
Ballistic energy transport
by spinons

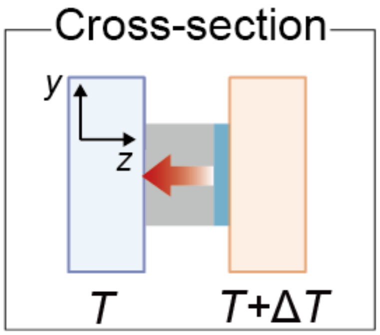
T. Kawamata, et al., JPSJ **77**, 034607 (2008)

Spinon spin Seebeck effect

【Experimental set-up】

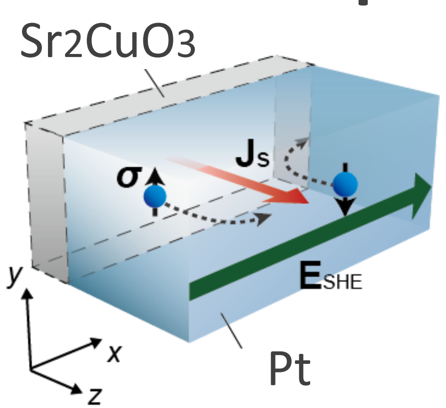




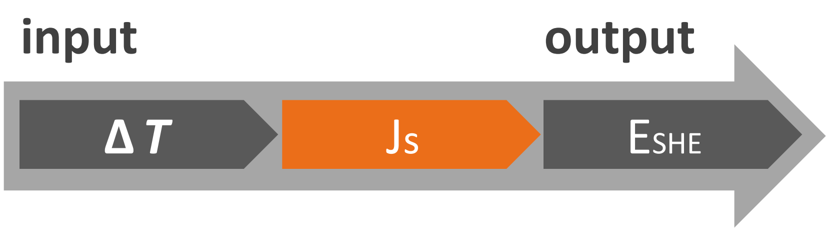


single crystal (**5N purity**)

【Detection of spin currents】



$E_{SHE} \propto J_s \times \sigma$



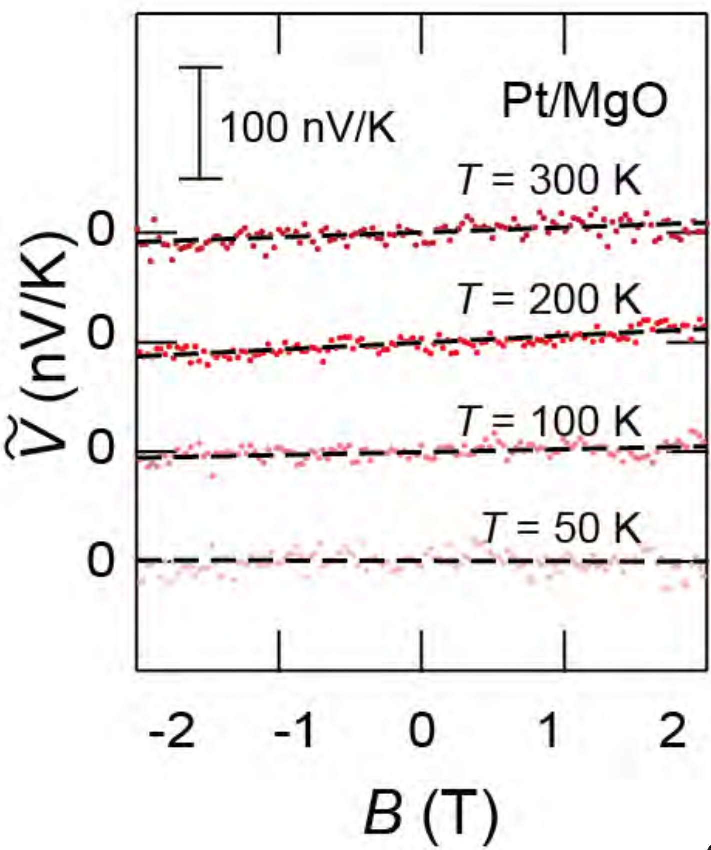
Detect spin currents electrically via the inverse spin Hall effect in Pt

➡ Measure *B*-, *T*-dependence of $\tilde{V} = V/\Delta T$

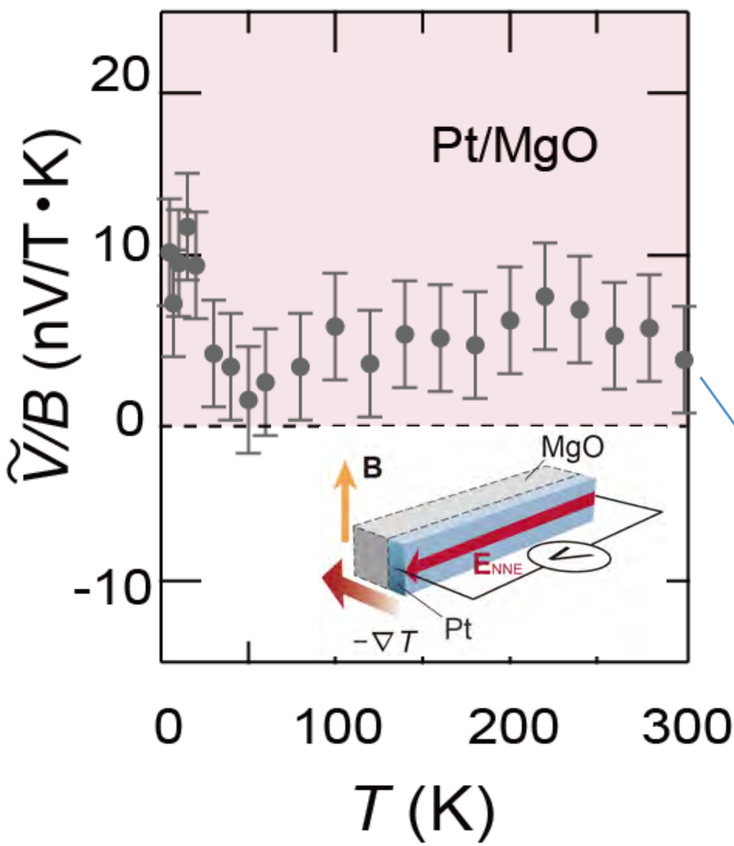
Δ*T*-induced voltage in Pt *without* Sr_2CuO_3

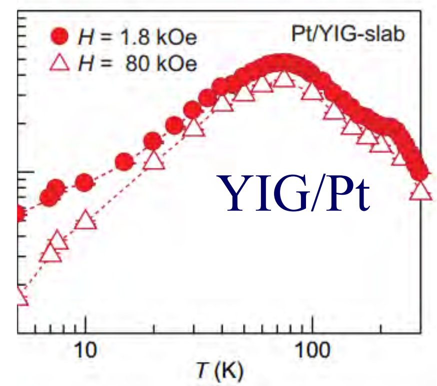
【normal Nernst effect in Pt】

Field dependence



Temp. dependence





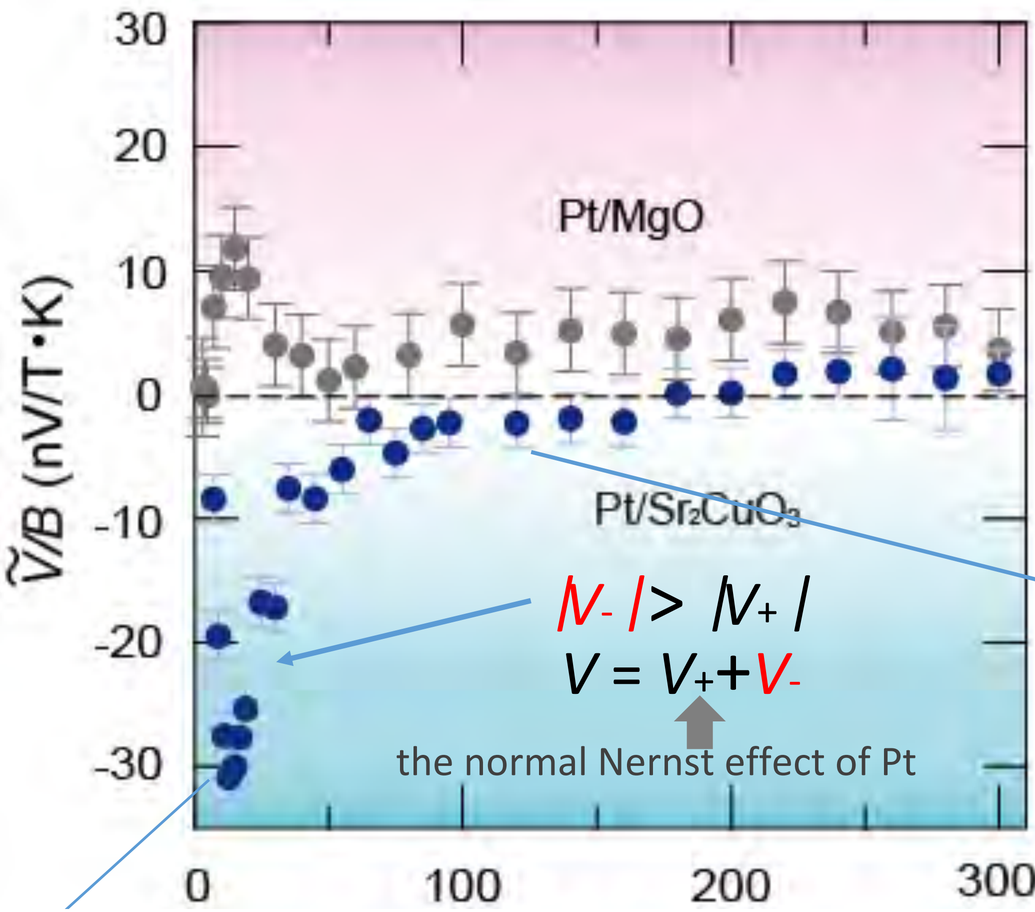
Proportional to field ; $\tilde{V}/B$ is **positive sign: same as YIG SSE**

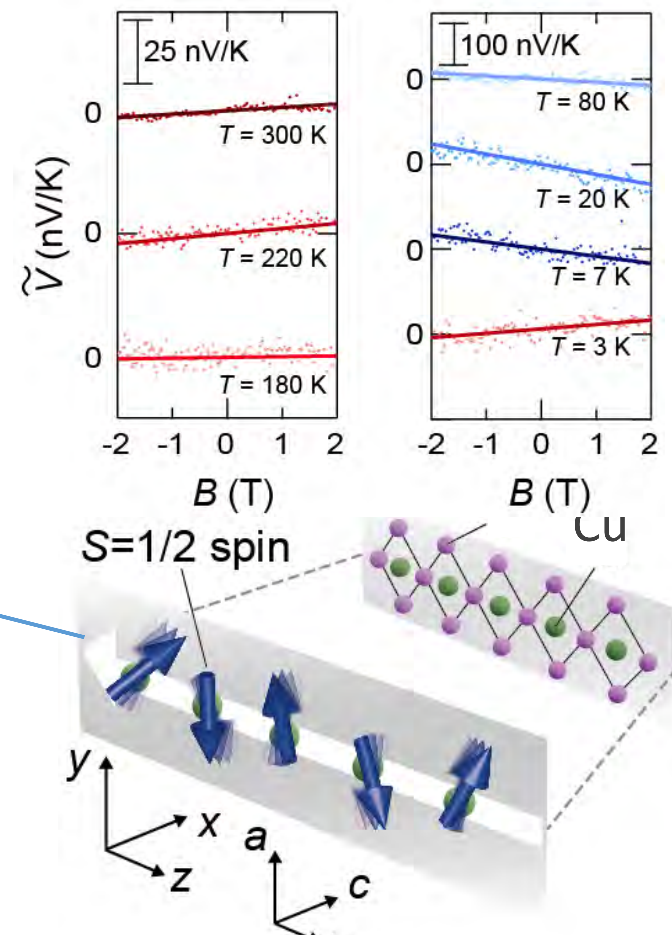
(consistent with the normal Nernst effect of bulk Pt)

ΔT-induced voltage in Pt *with* Sr_2CuO_3

Temp. dependence

Nature physics (in press)

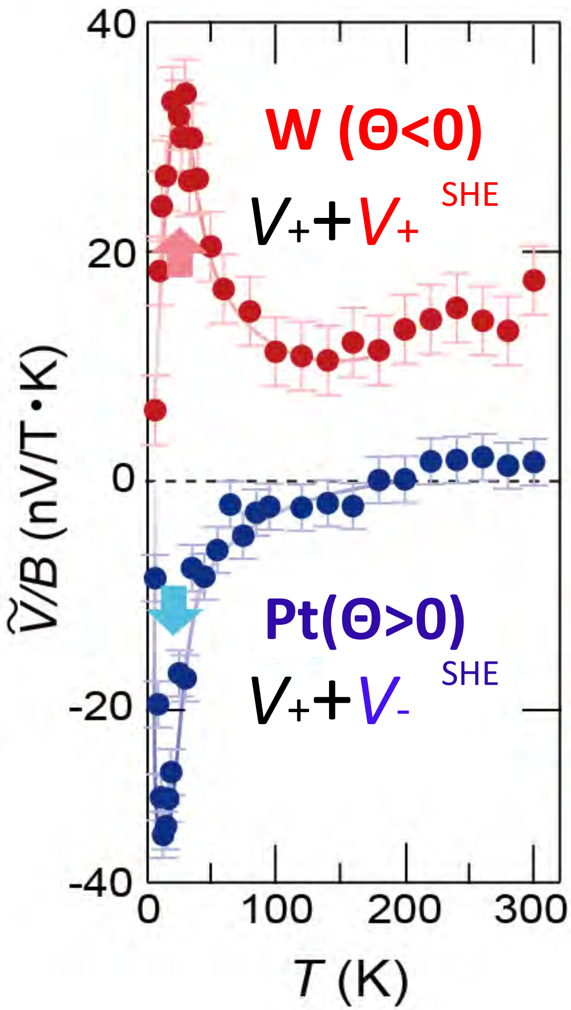




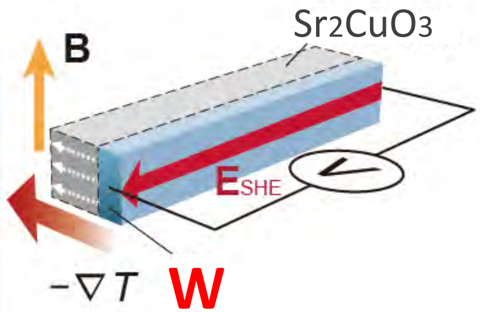
at low temperatures on Sr_2CuO_3, V component with Negative sign appeaers in addition to the ordinal Nernst effect (positive) in Pt

Check if the signal is due to spin current

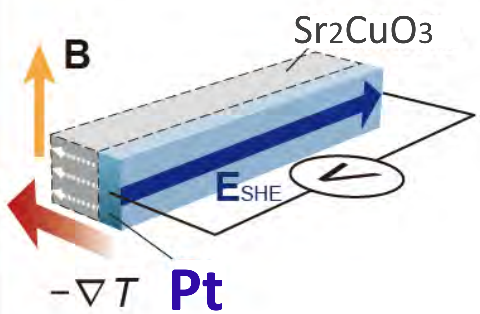
Temp. dependence



W/Sr2CuO3



Pt/Sr2CuO3



W & Pt convert spin currents into **opposite voltages** (opposite spin Hall angles)

\+

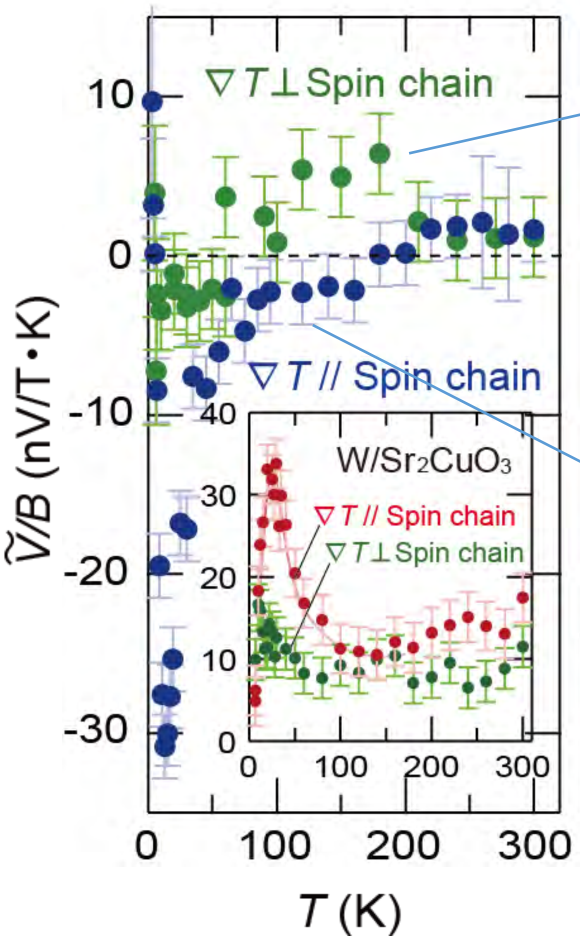
Positive peak for W/Sr_2CuO_3 in the vicinity of 20 K

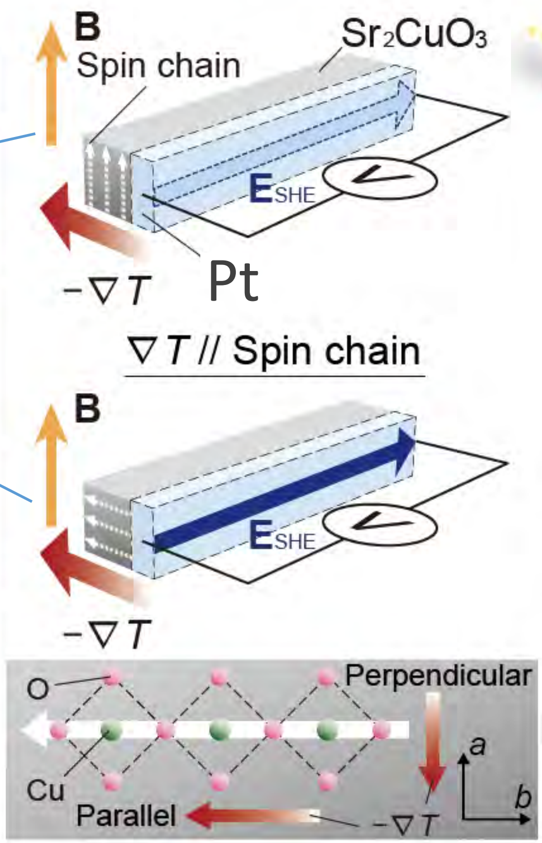
Negative voltage signals for Pt are due to **spin-current injection** from Sr_2CuO_3

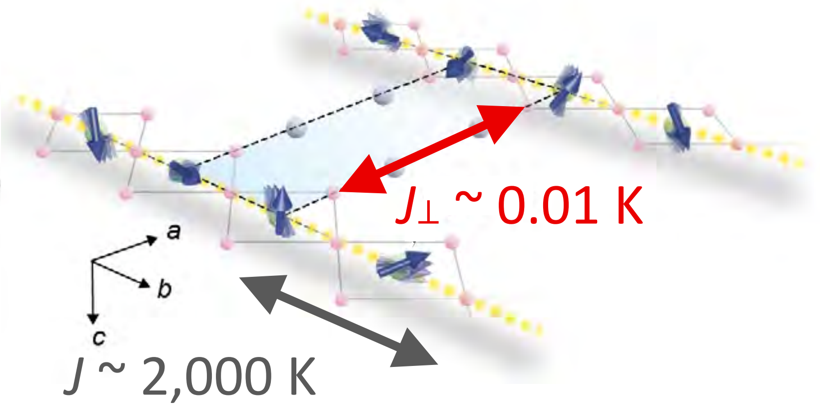
Nature physics (in press)

Along vs Across the spin chains

Temp. dependence







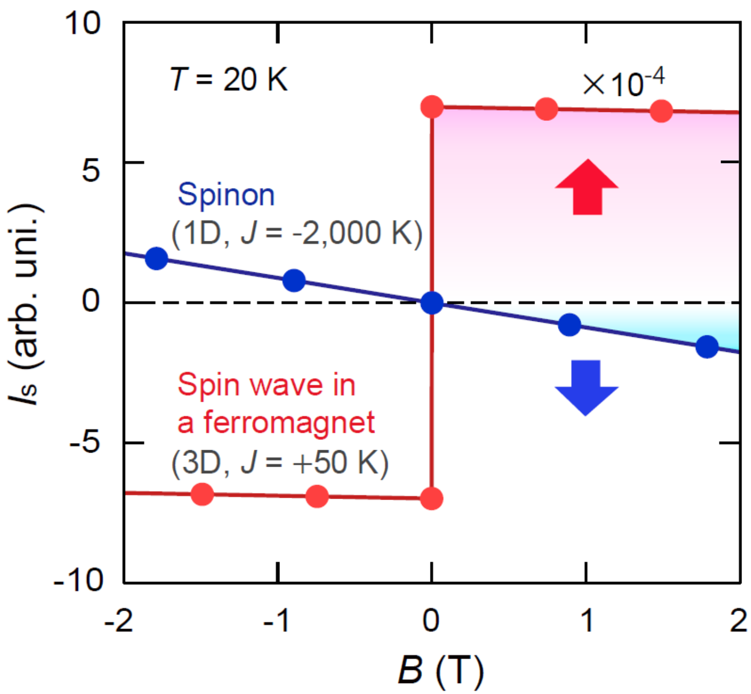
Suppression of spin-current injection
due to anisotropic spin correlation

Spin currents through spin chains dominate spin injection

Nature physics (in press)

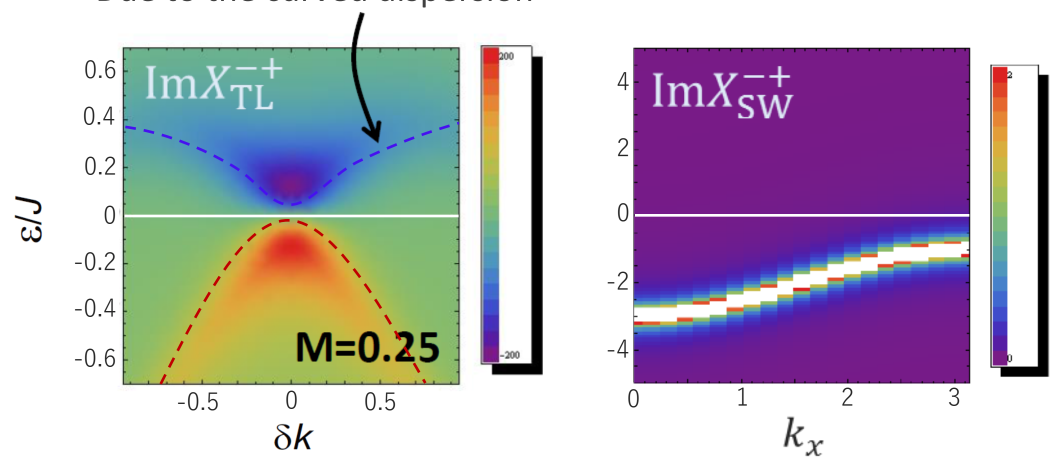
Comparison with a theoretical calculation

【Spin current vs. Field】



Spinons | **Ferromagnetic magnons**

Due to the curved dispersion



Greater weight in the **positive-ω region**

Greater weight in the **negative-ω region**

$$\tilde{I}_s = \frac{1}{T^2}\int_{-\infty}^{\infty} d\omega \boxed{\mathrm{Im}X^{-+}(\omega)} \frac{\omega^2}{1+\tau_s^2\omega^2}\frac{1}{\sinh^2(\omega/(2T))}$$

Nature physics (in press)

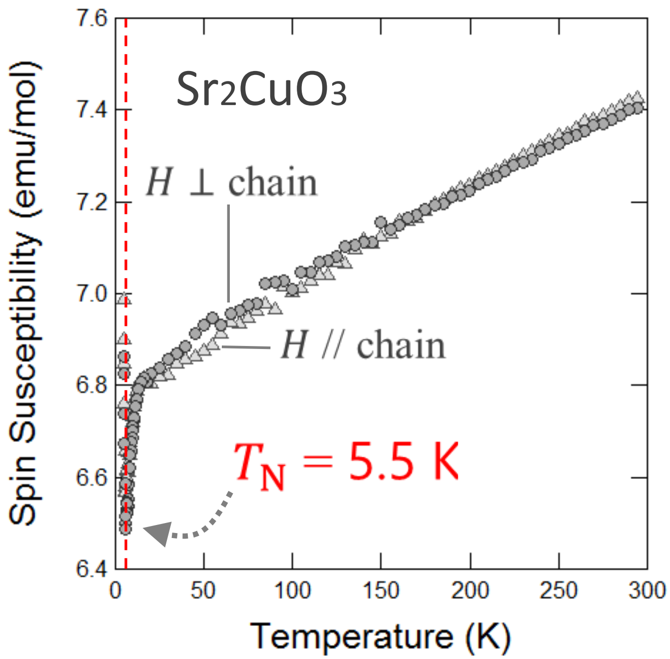
G. Muller, et al., Phys. Rev. B. **24**, 1429 (1981)

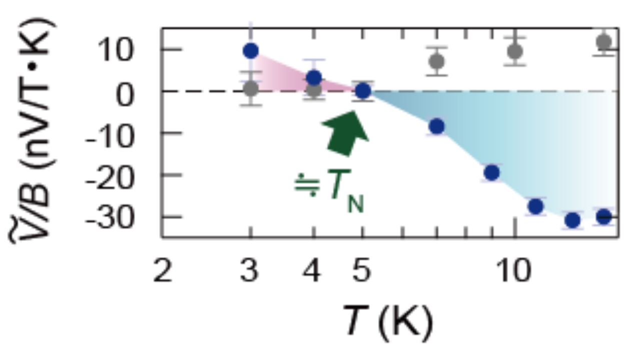
Expanded Bosonization method & Linear response by M. Sato

arXiv:1609.06410iv

Spinons vs. Antiferromagnetic magnons

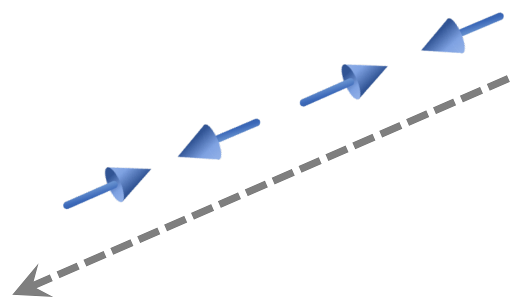
Magnetic susceptibility vs. Temp.





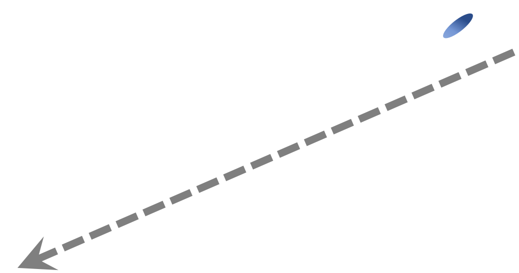
Spin configurations in each *T*-region

$T < T_N$ Antiferro.



Antiferromagnetic magnons **carry spin current**

$T_N < T$ 1D QSL

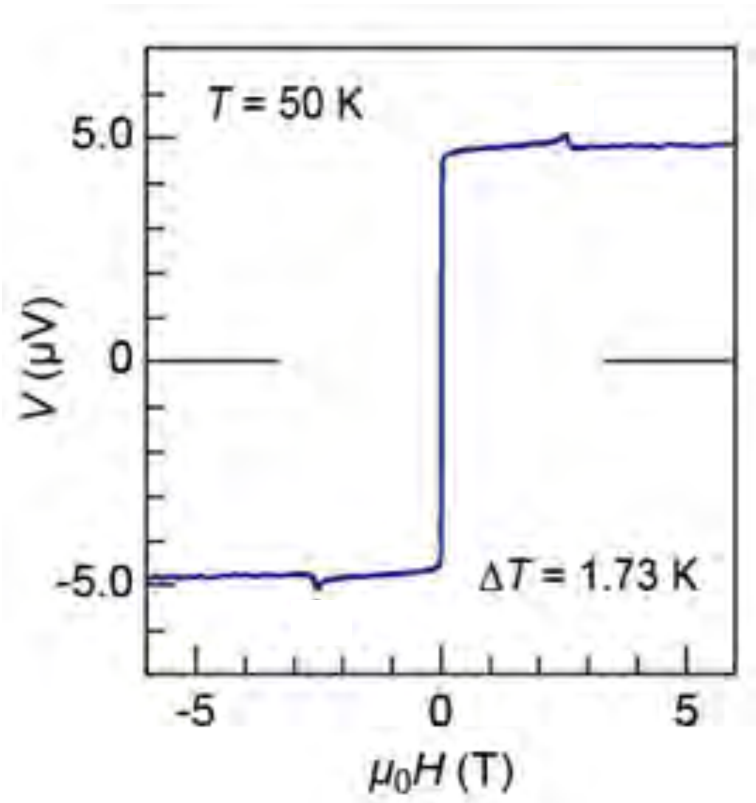


Spinons **carry spin current**

Ordered spins aligned along the spin chains below ~5

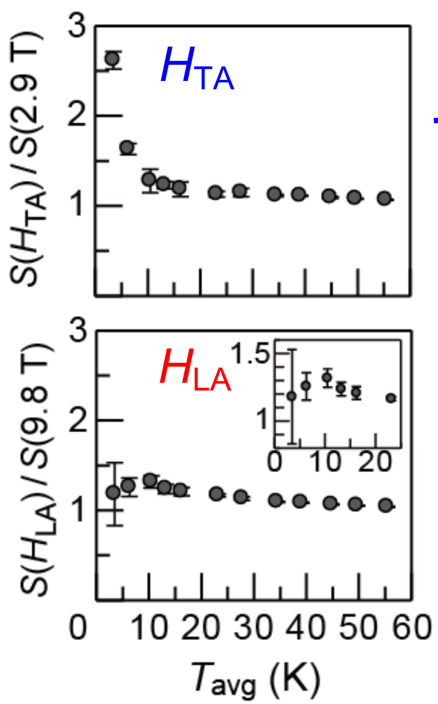
Spin Seebeck effect in a sputtered **Film** of YIG/Pt

- **High field resolution (ΔH=15mT)**

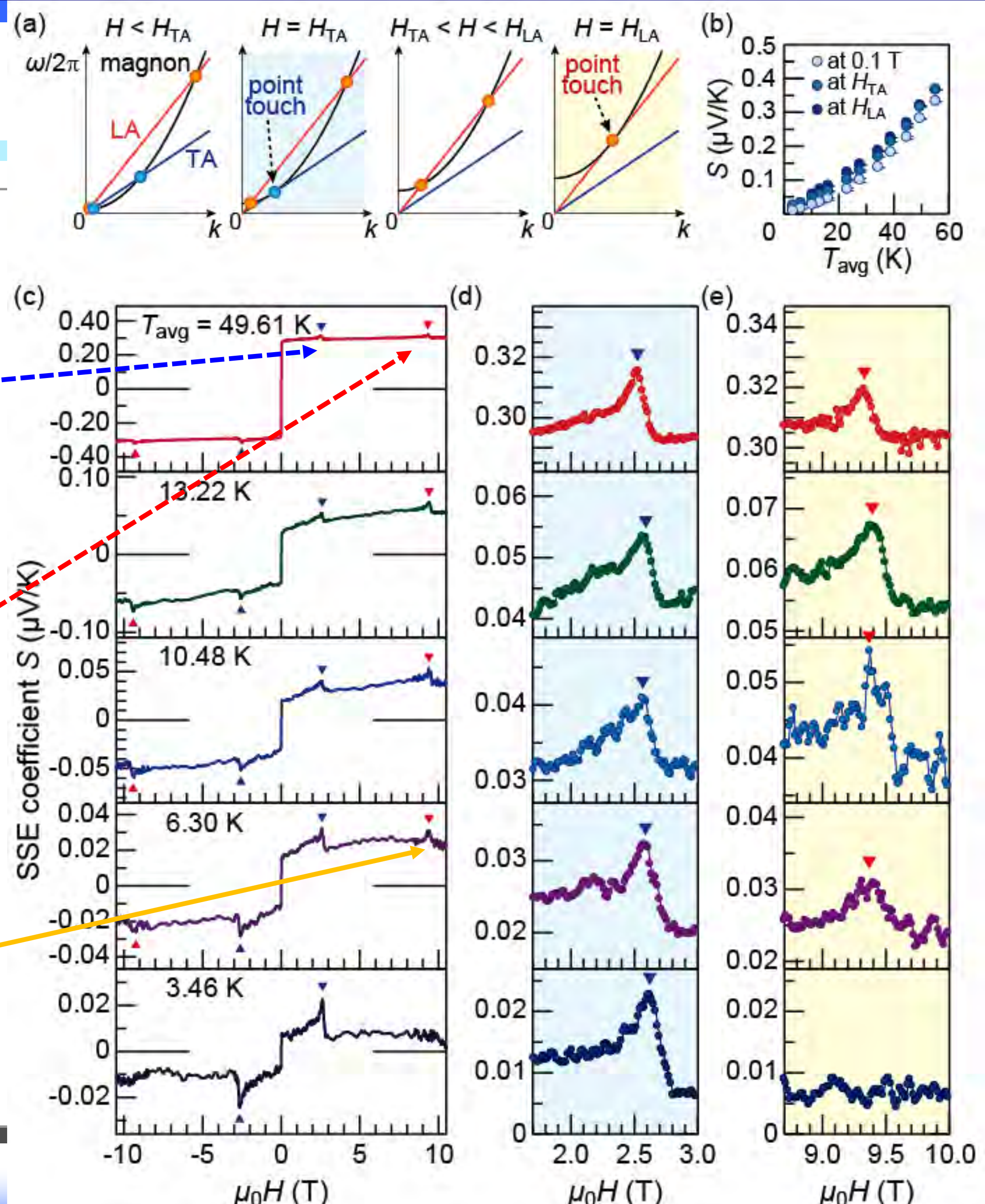


Temp. dep.

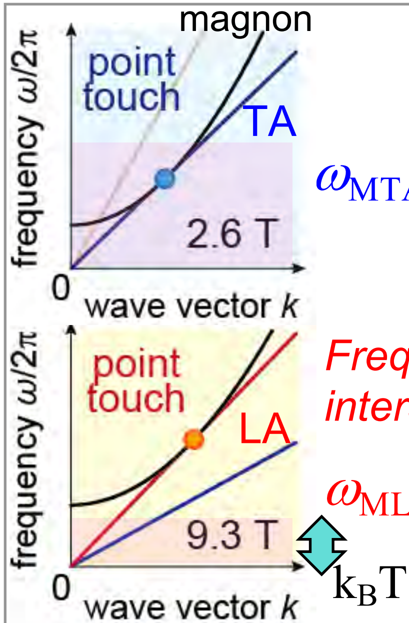
Relative peak strength



✓ peak at H_{LA}
is *suppressed*
(below ~ 10 K).



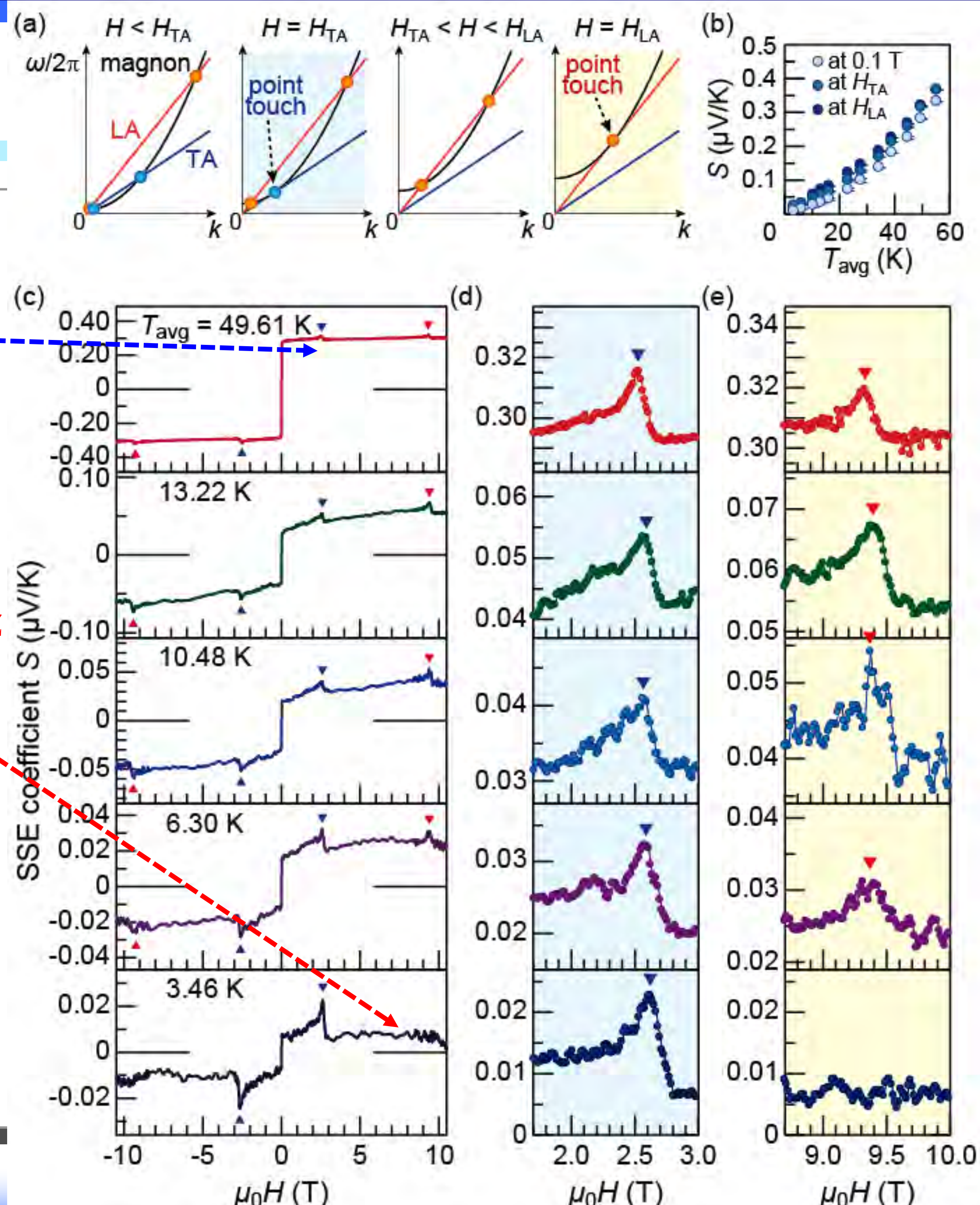
Temp. dep.



$\omega_{MTA}/2\pi = 0.16$ THz
(~ 7 K)

Frequency of the intersection

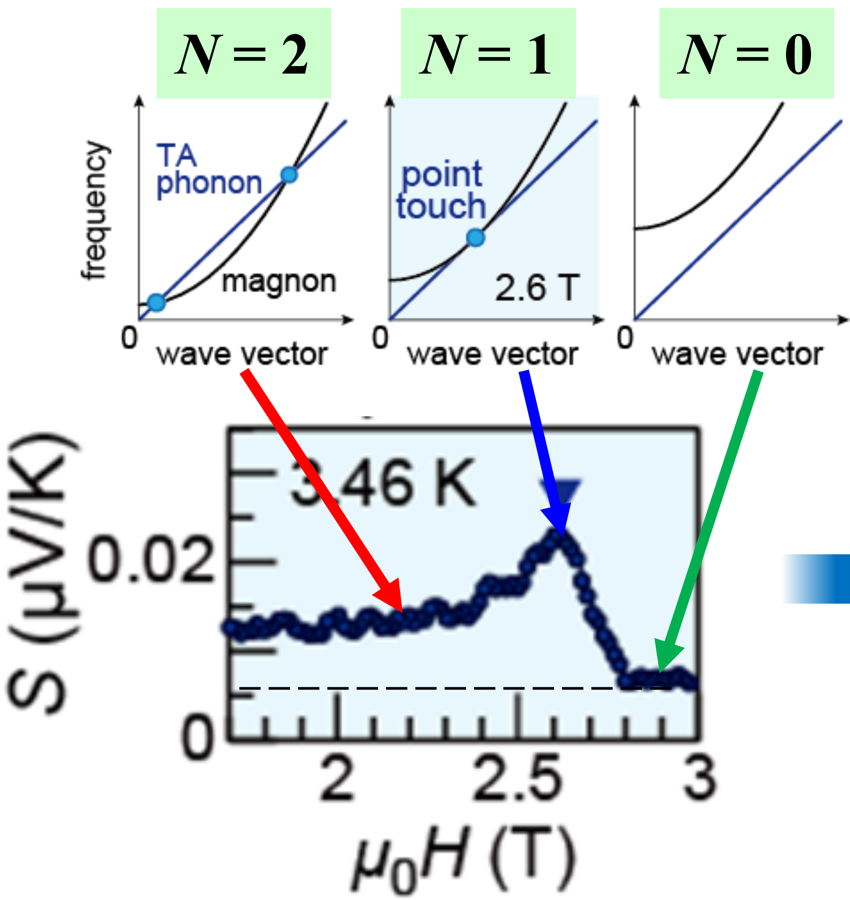
$\omega_{MLA}/2\pi = 0.53$ THz
(~ 20 K)



this suppression suggests that the thermal excitation of spin wave and phonon around this intersection is suppressed below $\hbar\omega_{MLA}/k$~26K, and thus the enhancement peaks vanish.

Information we can learn from the peak shape

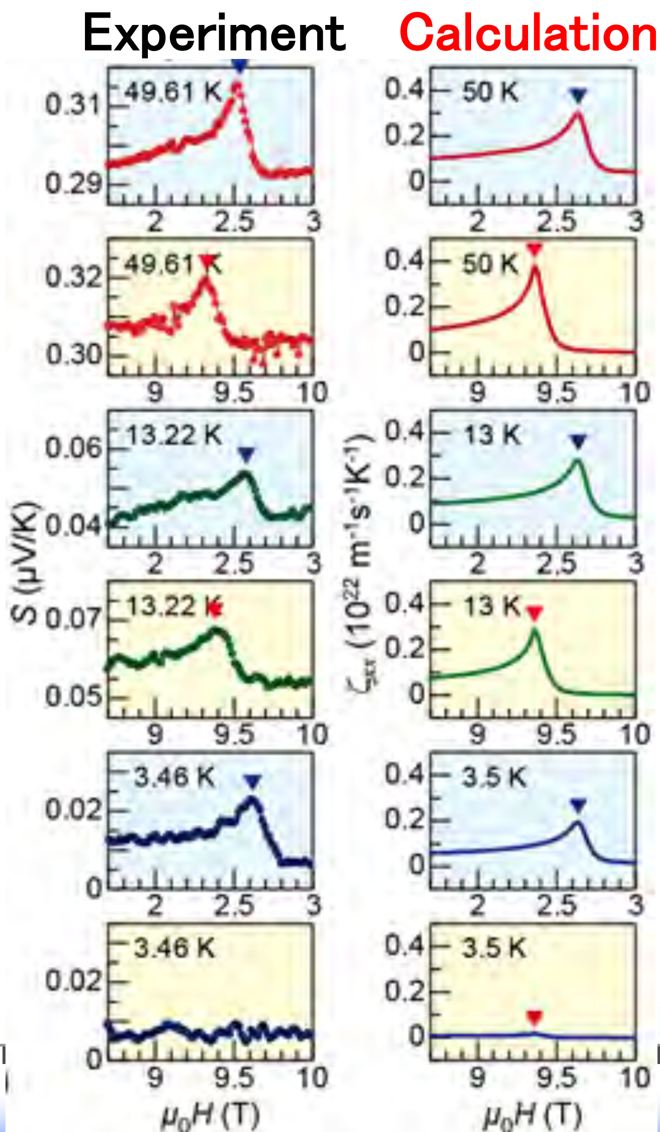
N: Number of the Crossing Point between magnon and phonon (TA)



Spin Seebeck intensity

$S(N=0) < S(N=2) < S(N=1)$

Comparison of peak shape with Theoretical Calculation



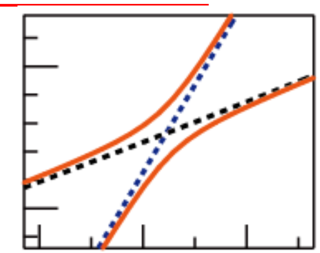
✓ Thermal spin-wave flow was calculated using a semi-classical transport theory in which *magneto-elastic coupling* is taken into consideration .

✓The theory shows that a spin-wave flow is enhanced via the hybridization with phonons, **when** $\tau_{\text{Phonon}} > \tau_{\text{Magnon}}$.

✓At the point-touching condition, the enhancement effect is maximized because of the **maximum phase-space volume** around the intersection points.

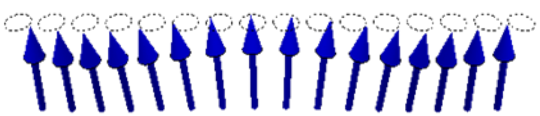
with K.Shen, B.Flebus, R.Duine, and G.Bauer

→ Shen Bauer Duine Flebus

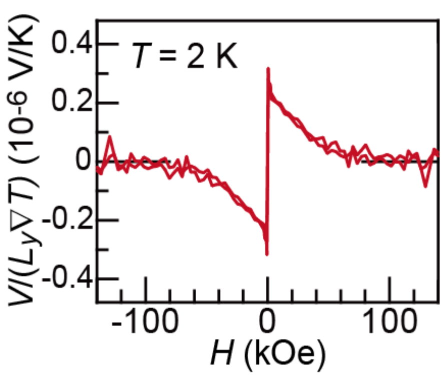


Summary

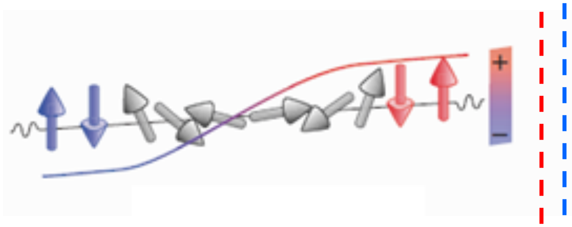
Magnons



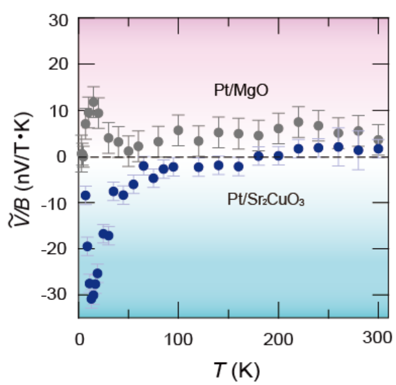
SSE of magnons



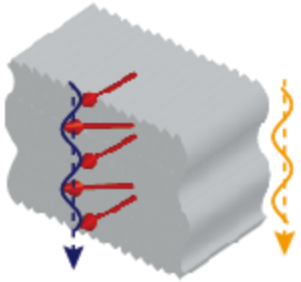
Spinons



Spinon SSE



Phonons



Phonon anomaly