Magnonics – a new frontier in Quantum Materials & Devices

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Quantum Materials

Strongly correlated electrons
Geometrical frustration
Multiferroics
Magnetoelectrics
Structure-property relationships

Spintronics

Spin currents in solids
Spin Caloritronics
Magnon Hall effect
Anomalous Nernst Effect
Ferromagnetic Resonance
Acoustic Spin Pumping

Instrumentation

Developing low temperature apparatus to enable these investigations.

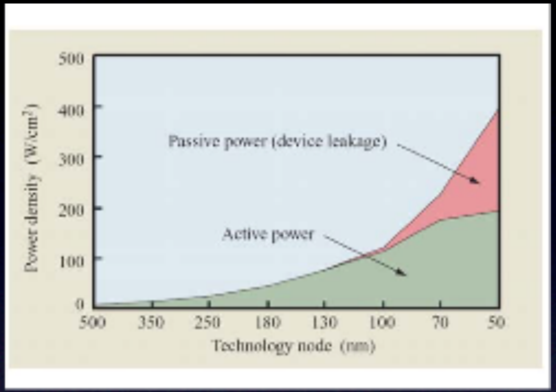
Outline

- ➢ Magnonics
  - Some History, Spin Currents, and their detection
  - Problems and Possible Artefacts
  - Potential use cases going forward
- ➢ Some of our own work
  - SSE measurements on LCMO/Pt
  - Electrical detection of surface magnons

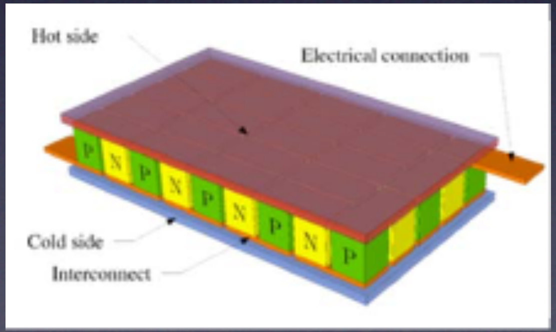
Approximate Nomenclature

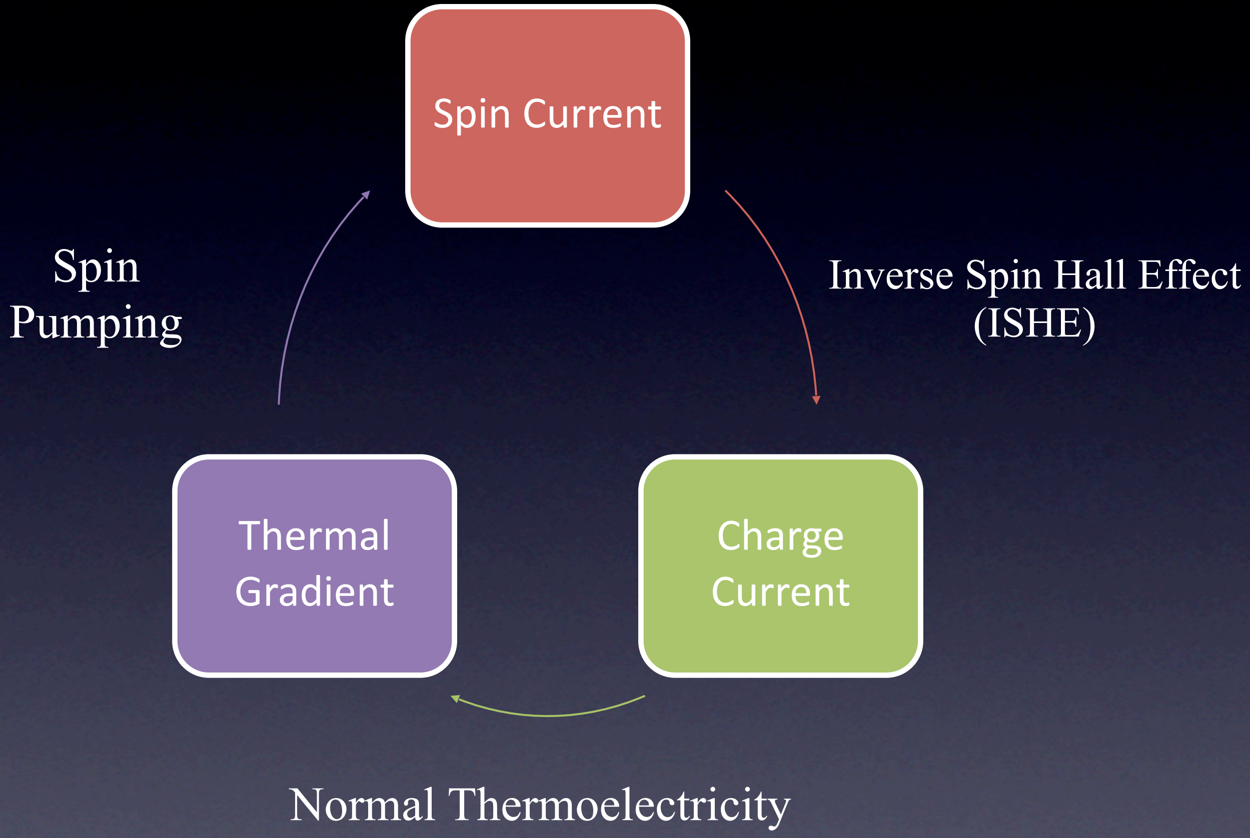
Area of Research	***Topic***
Electronics	Transport / Manipulation of Charge
Spin Electronics or Spintronics	Transport / Manipulation of Charge and Spin
Calorimetry	Study / measure the heat of chemical reactions or physical processes
Spin Caloritronics	Transport/ Manipulation of charge, spin via heat
Magnonics	Transport / Manipulation of spin wave quanta - or magnons

The emergence of Spin Caloritronics



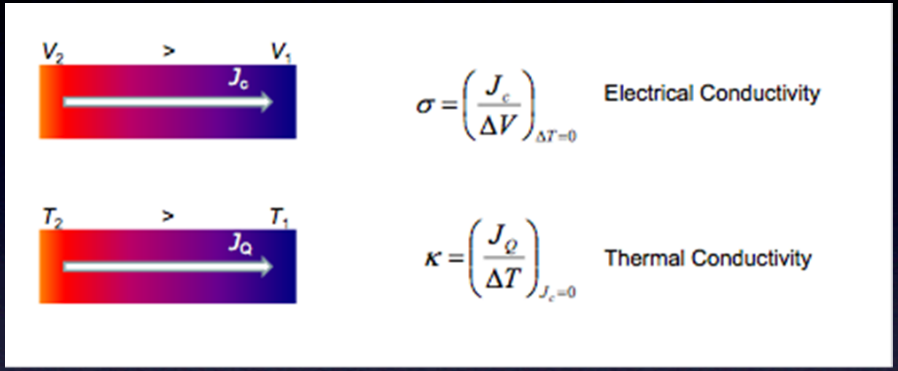
Energy Harvesting:

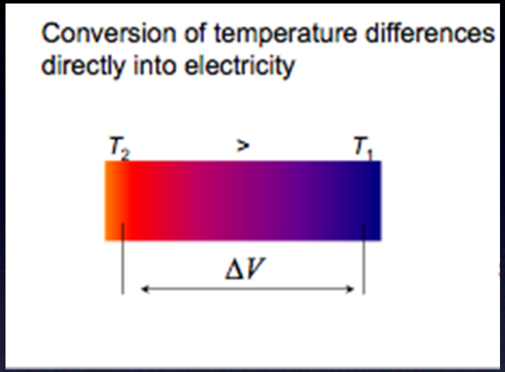




Starting of as an offshoot of thermoelectricity

Charge and heat currents





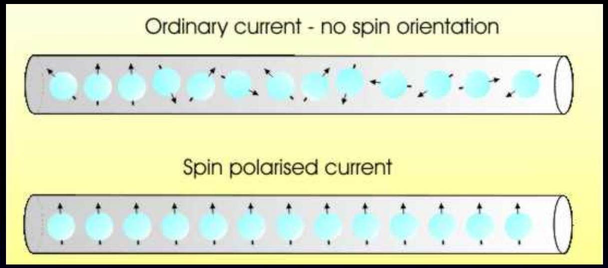
$$\frac{\kappa}{\sigma} = LT$$

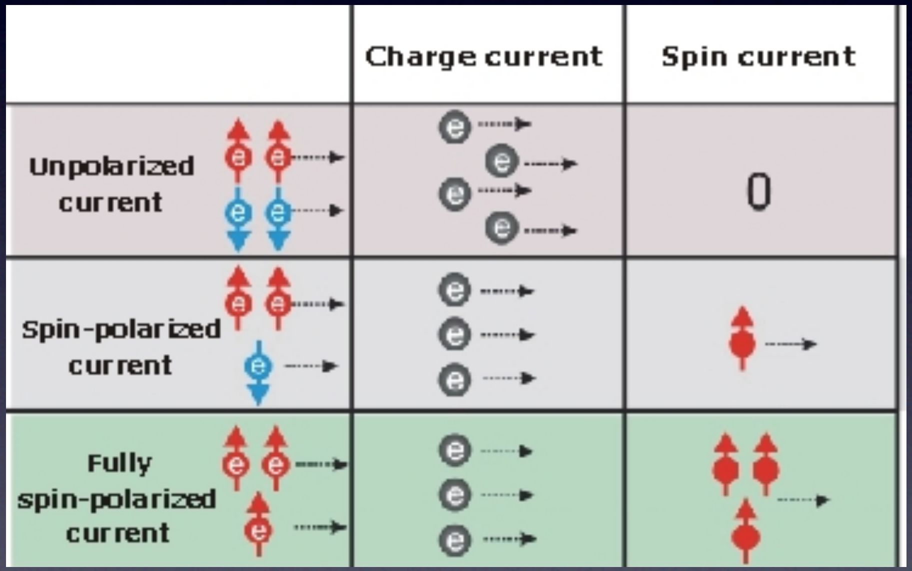
Wiedemann-Franz Law

$$S = \left(\frac{\Delta V}{\Delta T}\right)$$

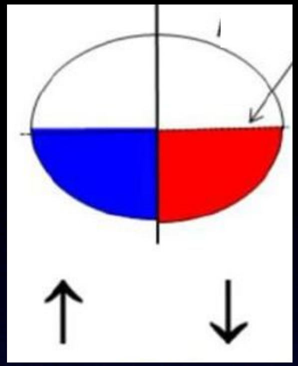
The Seebeck Co-efficient

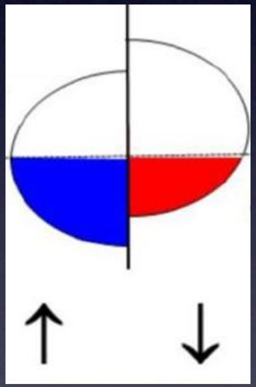
Spin currents in solids

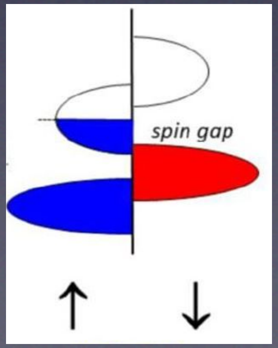




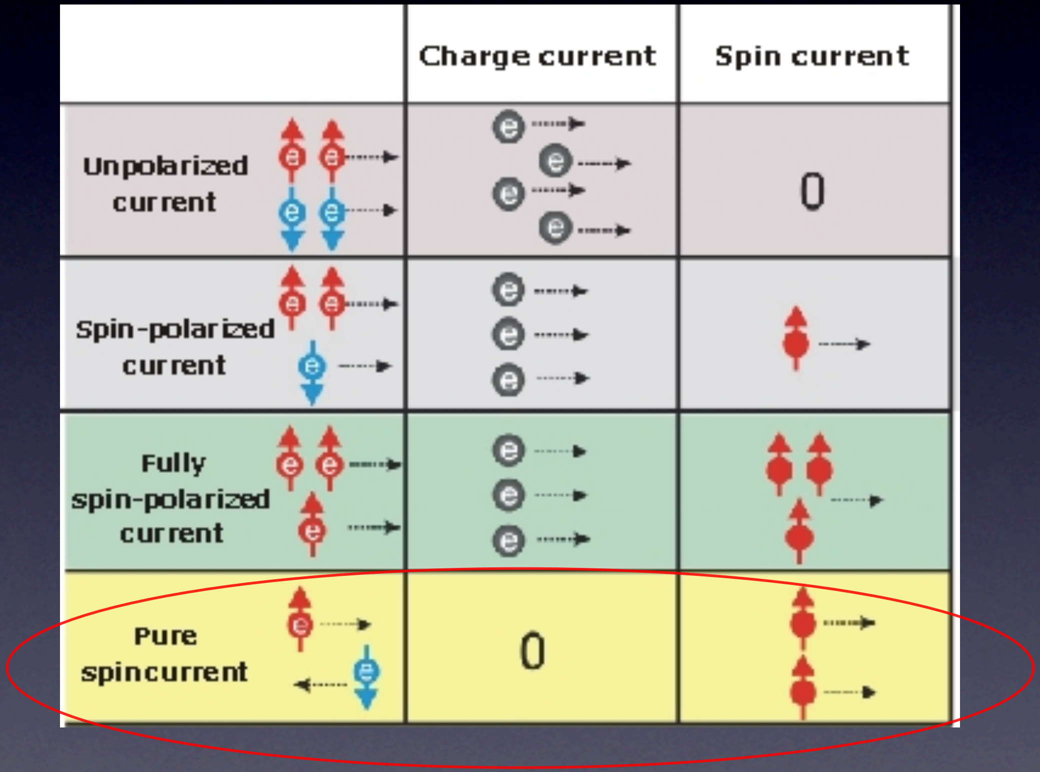
http://ssp.phys.kyushu-u.ac.jp



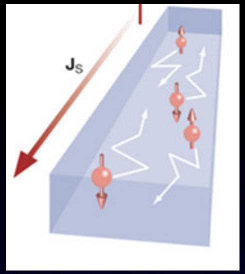




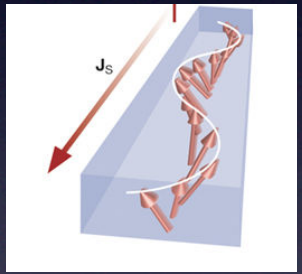
Spin currents in solids



	Charge current	Spin current
Unpolarized current		0
Spin-polarized current		
Fully spin-polarized current		
Pure spincurrent	0	



Spin Dependent transport



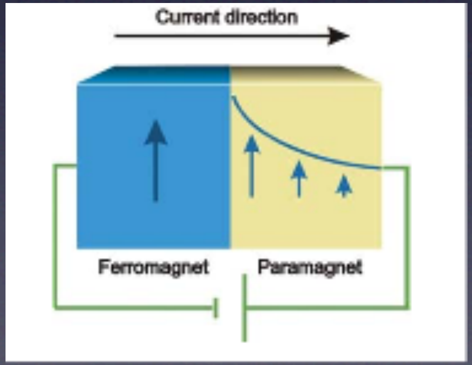
Pure Spin transport

Transfer of Spin Orbital momenta

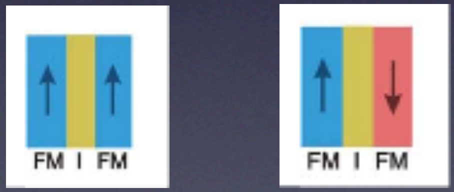
Why use the Spin Current ?

Charge Current: Moving charge
Dissipation

Spin Current: Charge does not have to move
relatively dissipation-less



Spin Polarised Current in a nonmagnetic metal

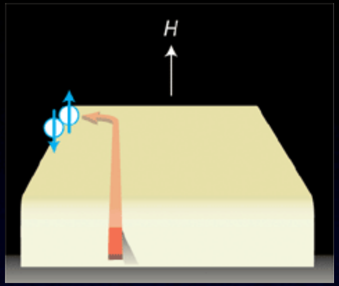


Spin Polarised Current through a magnetic tunnel junction

Electrical & Thermal driven Spin effects

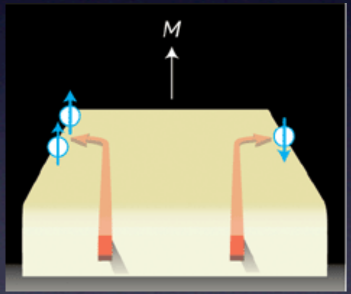
With $\vec{E}$

Hall Effect



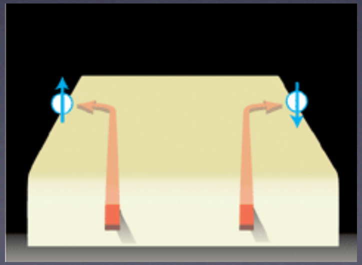
H ≠ 0, M = 0

Anomalous Hall Effect



H =0, M ≠ 0

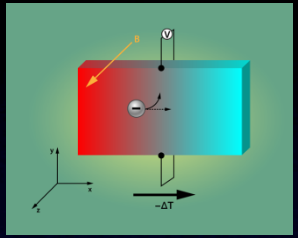
Spin Hall Effect



H = 0, M = 0

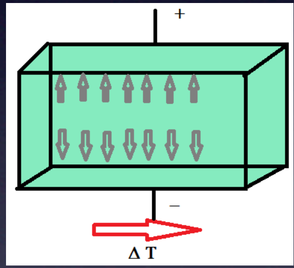
With ∇T

Nernst Effect



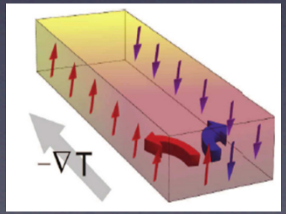
H ≠ 0, M = 0

Anomalous Nernst Effect



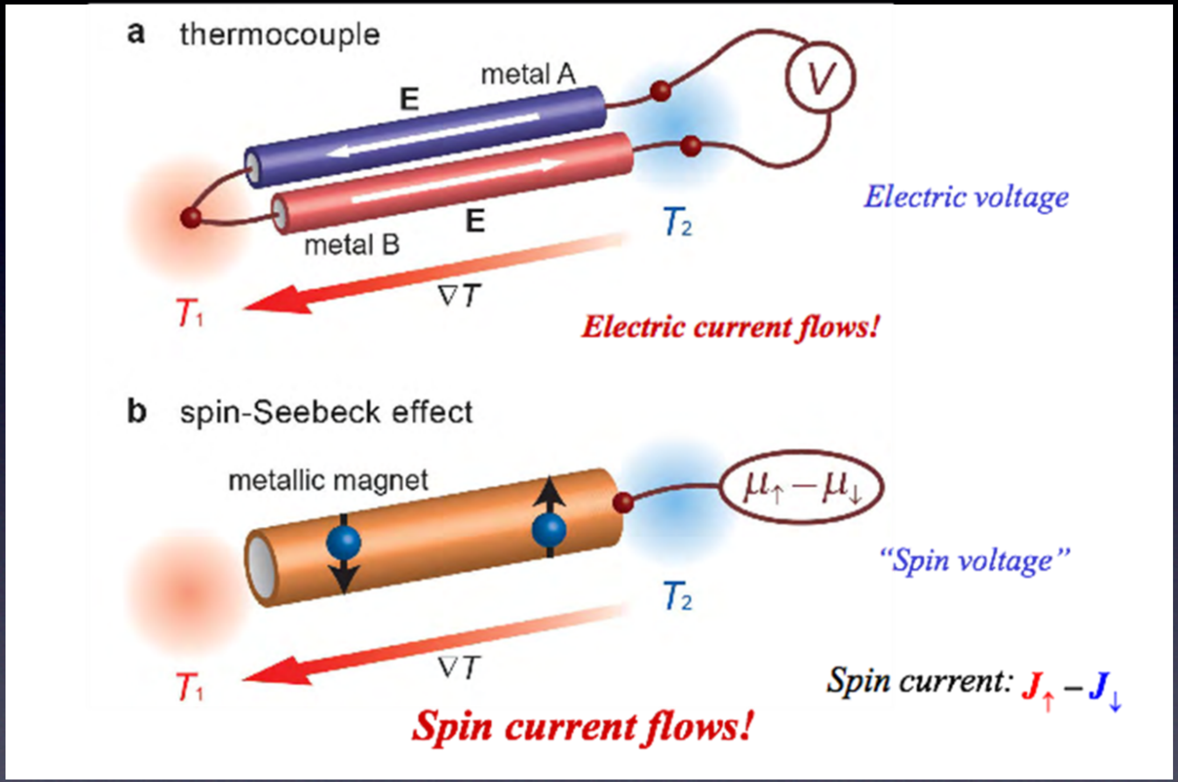
H =0, M ≠ 0

Spin Nernst Effect



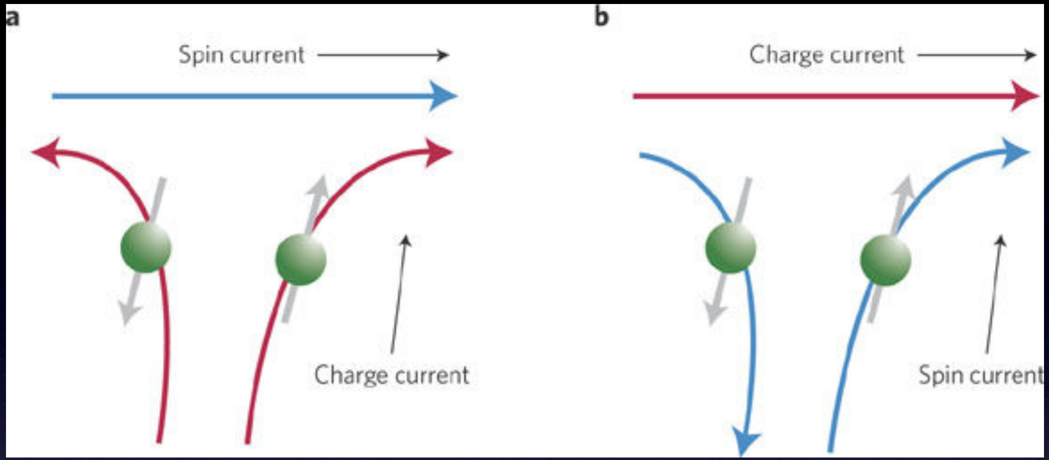
H = 0, M = 0

Spin Caloritronics: The Spin Seebeck effect

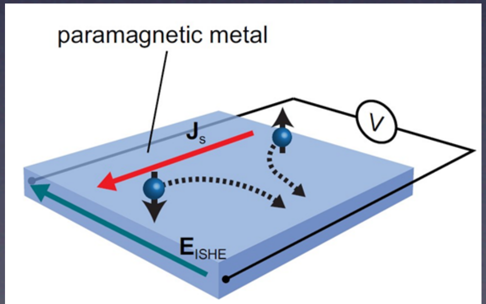


K Uchida *et al.* *Nature* **455**, 778-781 (2008)

On measuring the Spin Seebeck effect



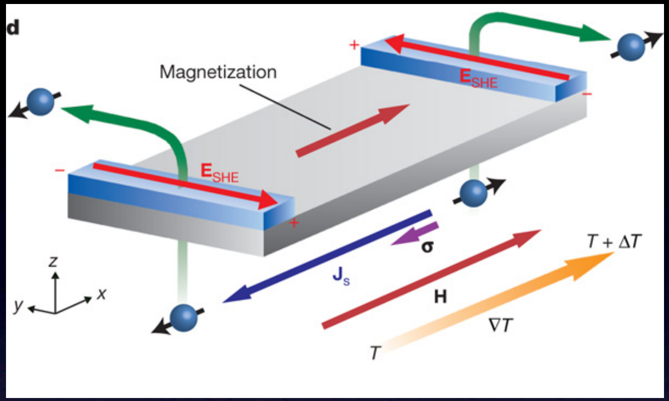
The inverse Spin Hall Effect

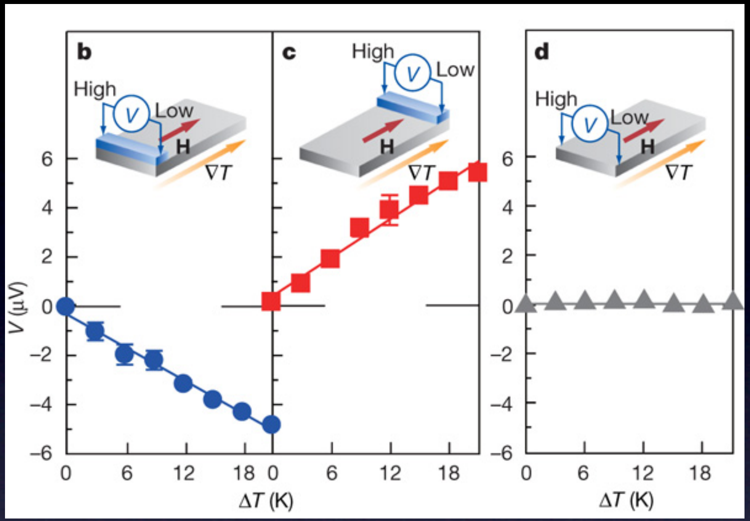


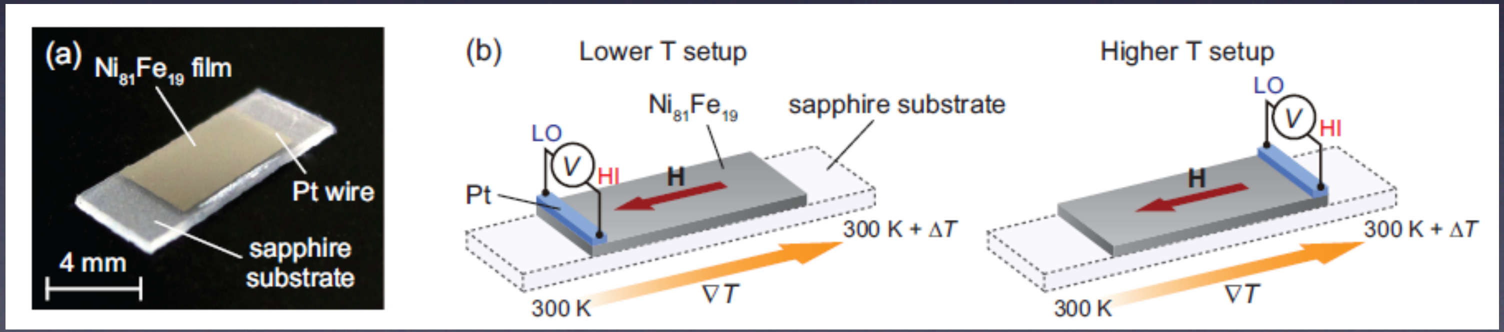
A paramagnetic metal with large SOC
Pt, Ta, etc

$$E_{ISHE} = (\theta SH\ \rho)\ Js \times \sigma$$

The first observation of Spin Seebeck effect

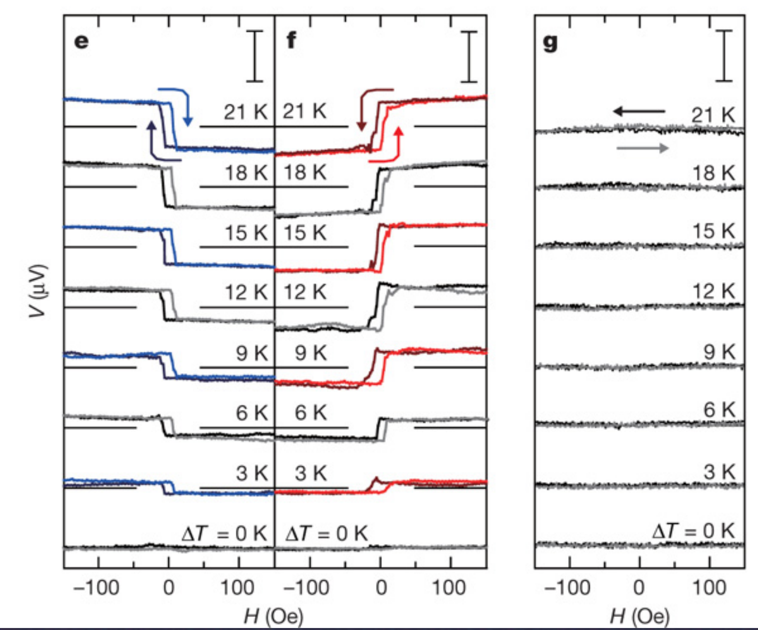


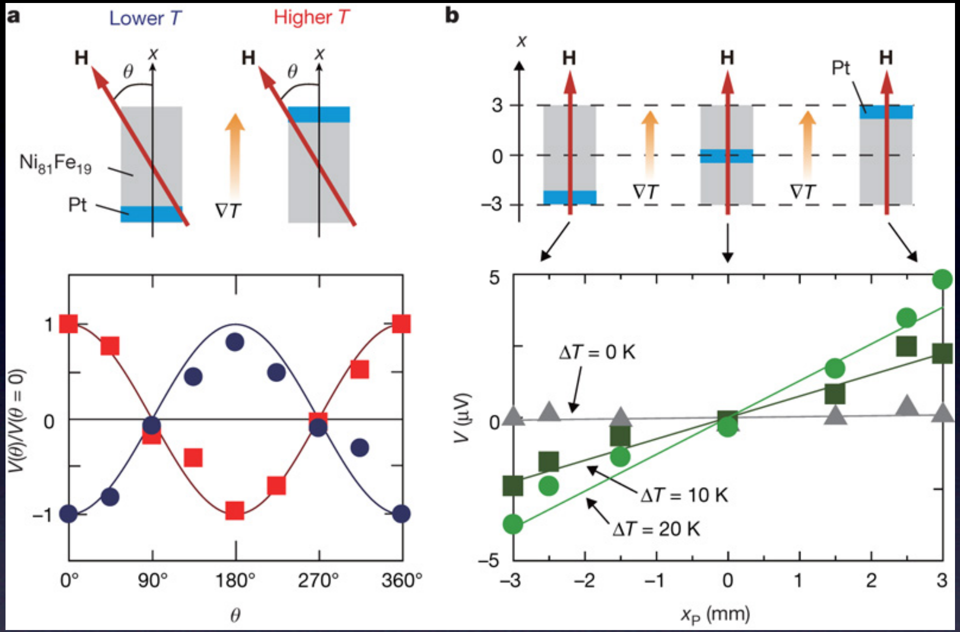




K Uchida *et al.* *Nature* **455**, 778-781 (2008)

The first observation of Spin Seebeck effect

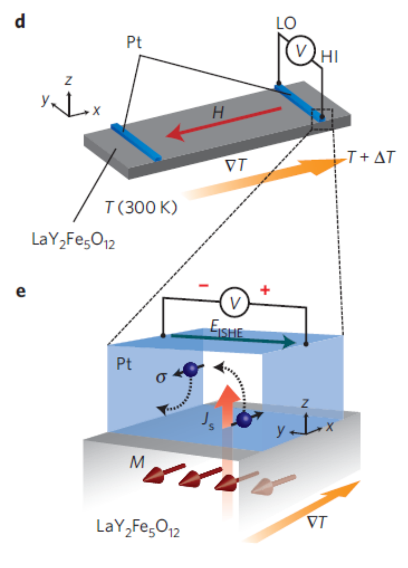


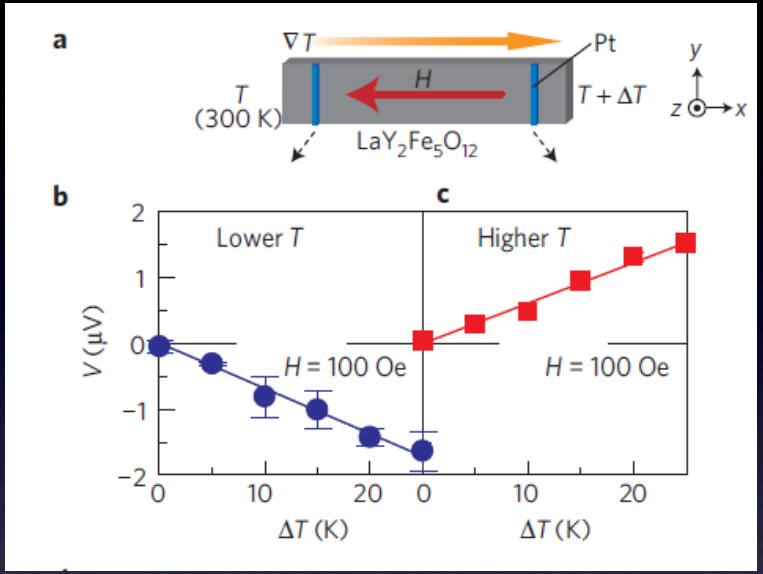


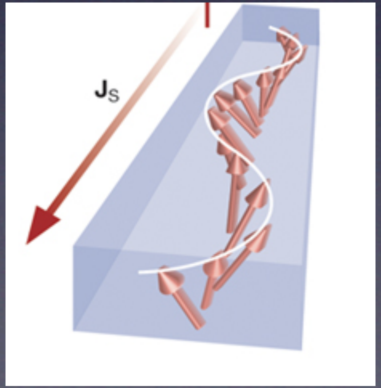
Dependence with Field, angle, distance etc….

K Uchida *et al.* *Nature* **455**, 778-781 (2008)

The Spin Seebeck effect in non-metals





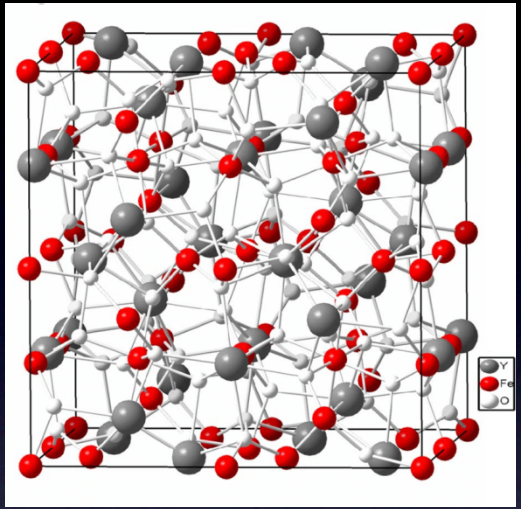


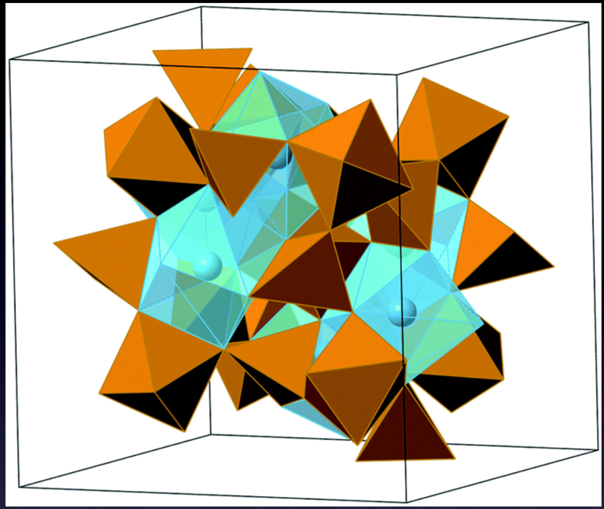
Absence of conduction electrons

True magnonic spin current

K Uchida *et al.* *Nature Materials* **455**, 894 (2010)

YIG-Pt: Model systems



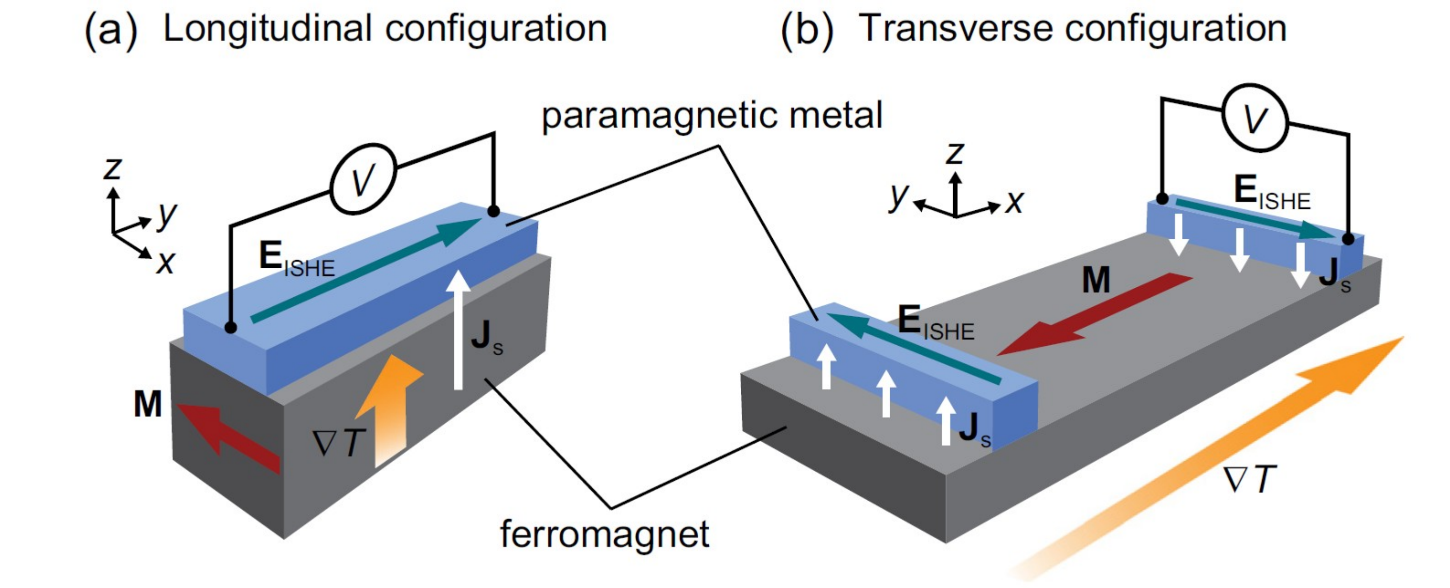


Yttrium Iron Garnet $Y_3Fe_5O_{12}$

Ferrimagnet, with $T_C \sim 560$ K

Room temperature insulator – ideal for SSE measurements

Measurement Geometries

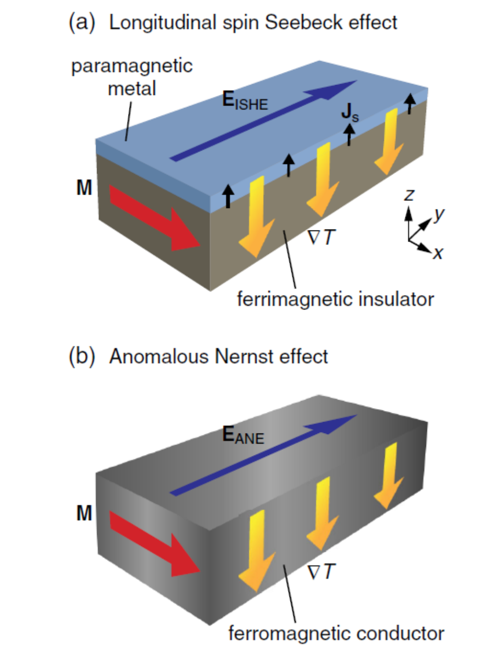


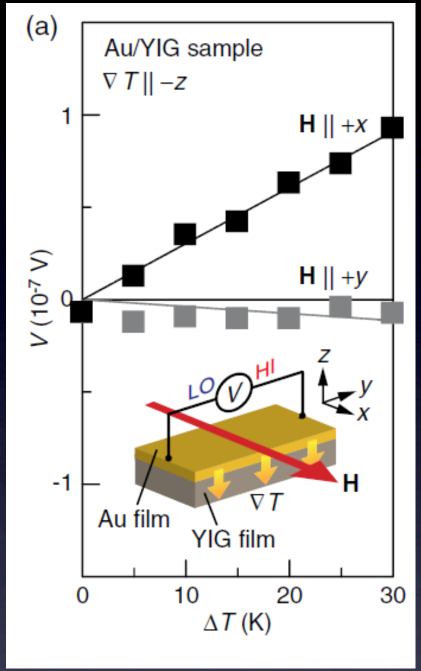
The Longitudinal configuration appears more flexible & gives more reproducible results

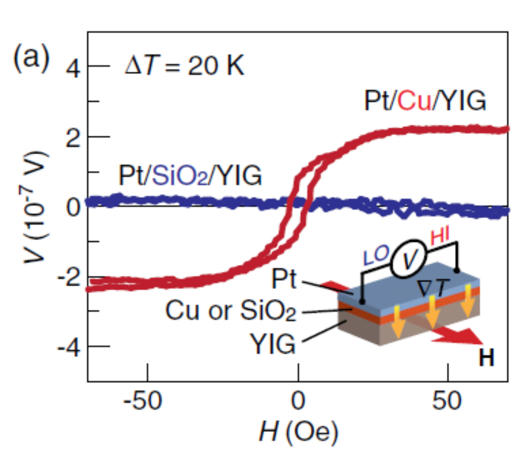
The transverse configuration no longer the preferred choice

The problem of ANE

Are LSSE signals contaminated ?







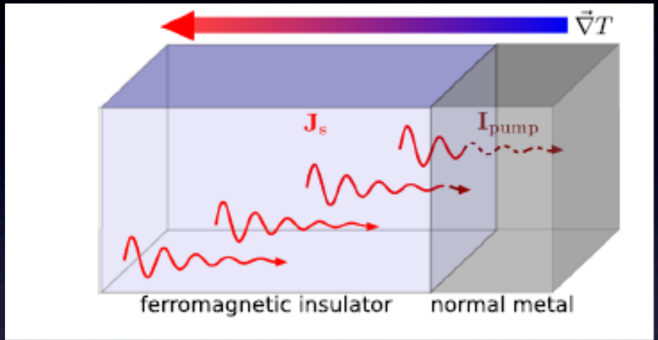
T. Kikkawa *et al.*
PRL **110**, 067207 (2013)

LSSE effect is intrinsic

The ANE contribution is negligible

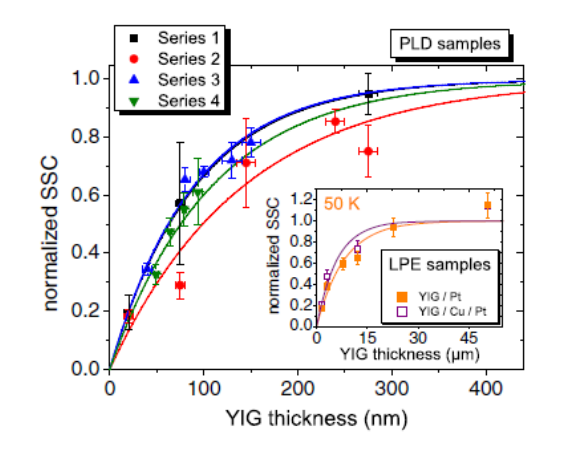
Interface or Bulk ?

Is there a thickness dependence ?

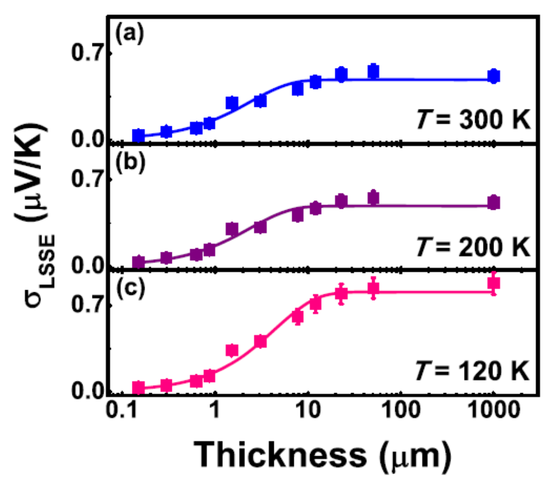


$$V_{LSSE} \propto 1 - e^{\left(-\frac{L}{\xi}\right)}$$

Length scale set by the magnon propagation length

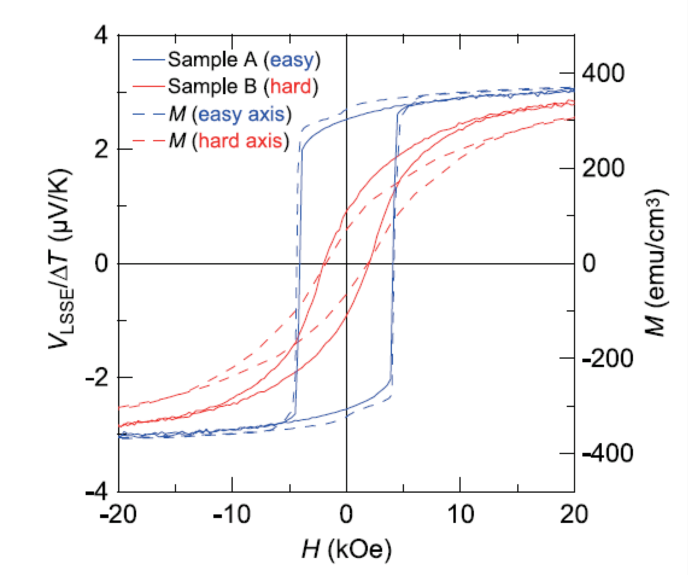


PRL **115**, 096602 (2015)



PRX **6**, 031012 (2016)

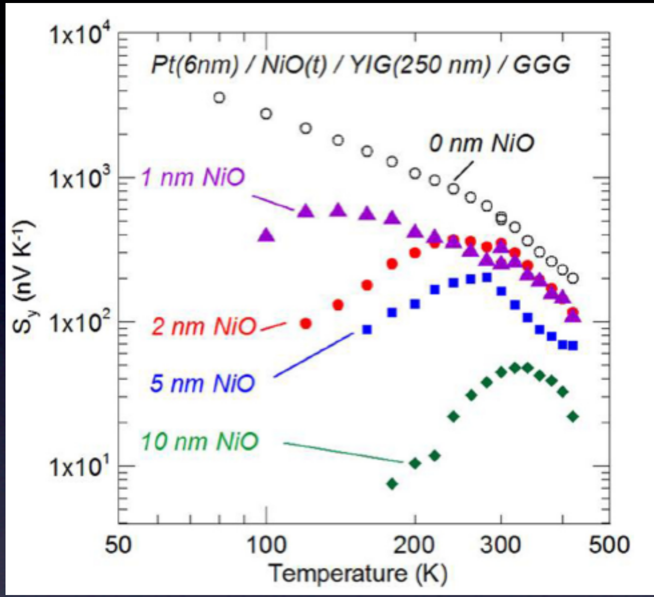
Utility: a measure of the magnetisation



Pt/CFO

The measured SSE faithfully reproduces the sample magnetisation

AIP Advances **5**, 053603 (2015)

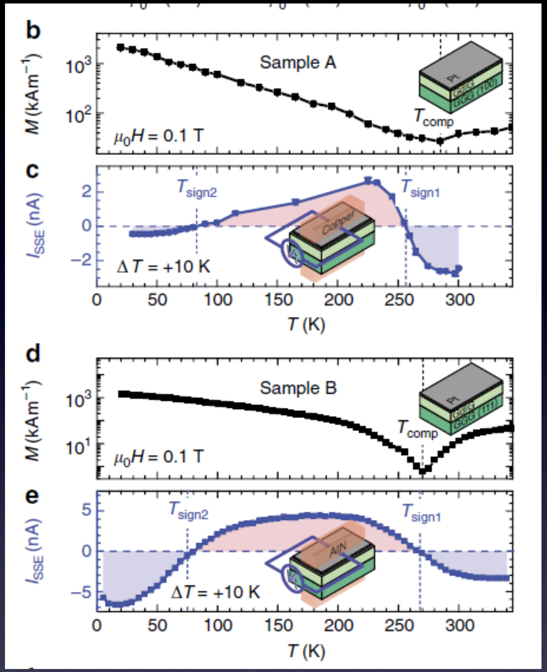


Pt/YIG/NiO

NiO is most transparent to magnon propagation in the vicinity of the magnetic transition

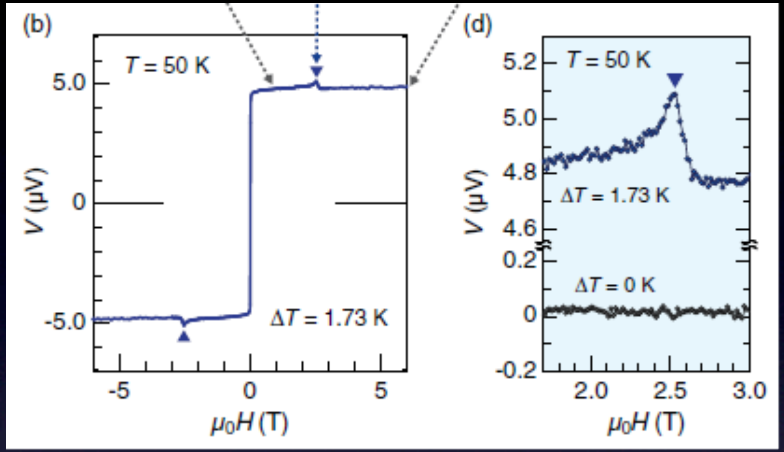
PRB **94**, 014427 (2016)

Utility: more than just the magnetisation



Compensated antiferromagnets

Nature Communications **7**, 10452 (2016)

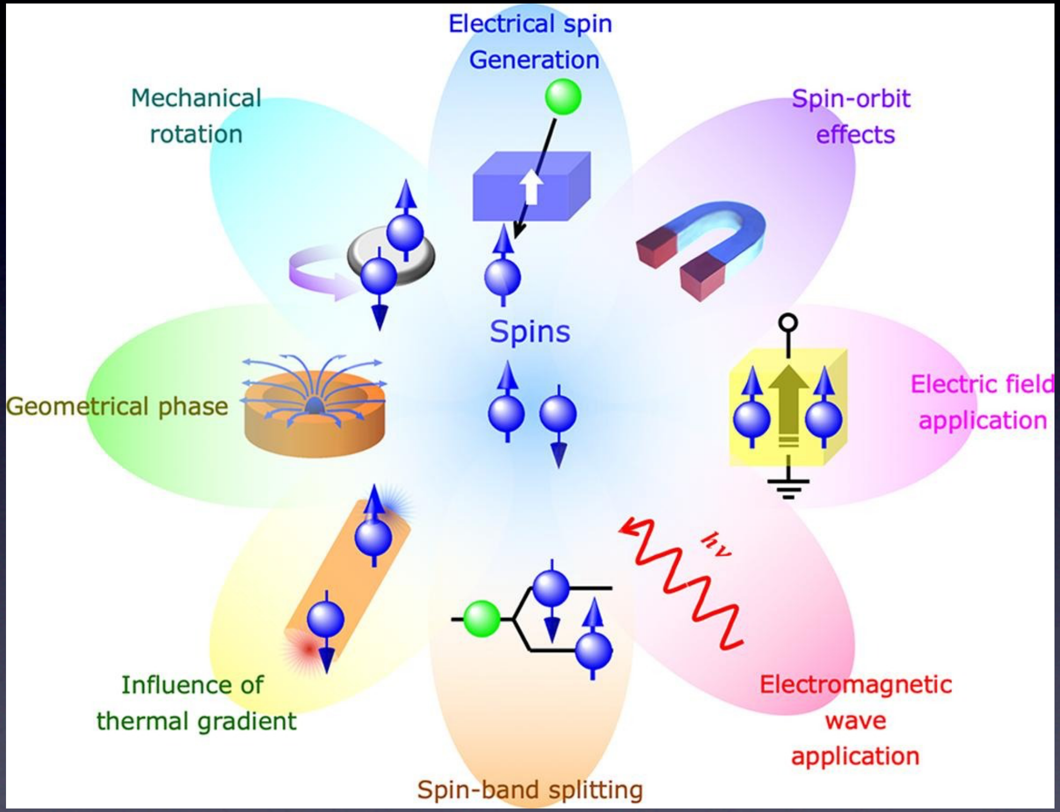


Magnon Polaron interactions

PRL **117**, 207203 (2016)

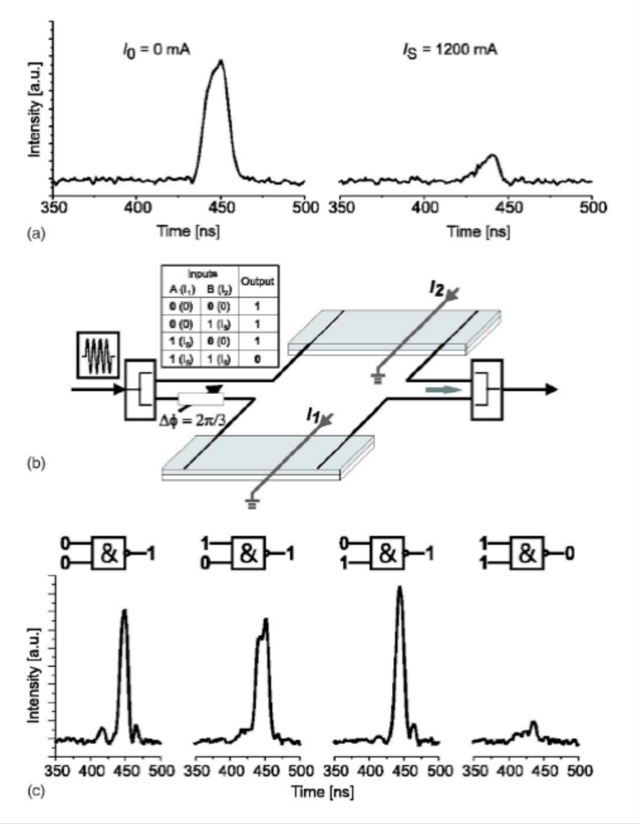
Spin Currents as a microscopic probe of materials & phenomena

Spin current generation

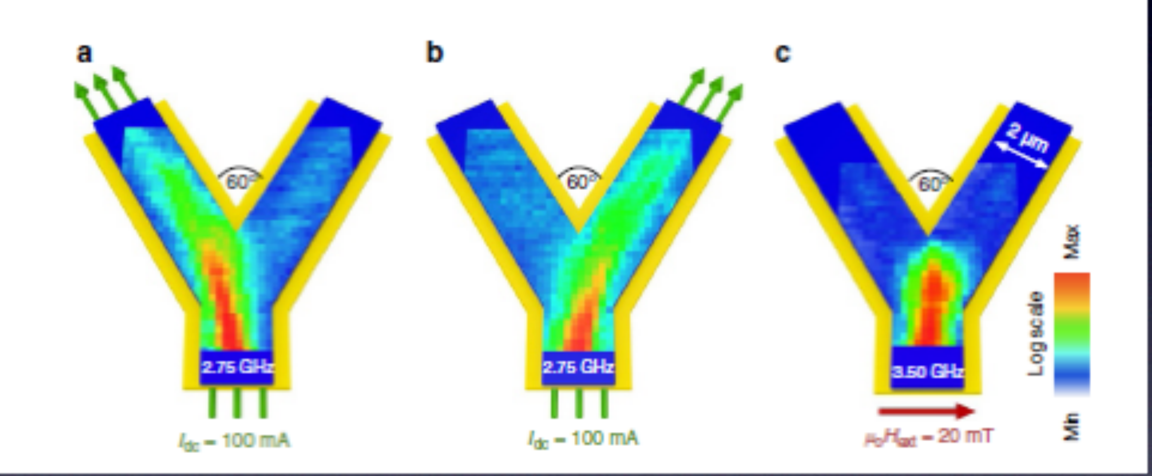


JMMM **509**, 166711 (2020)

Magnonic Curcuit Elements

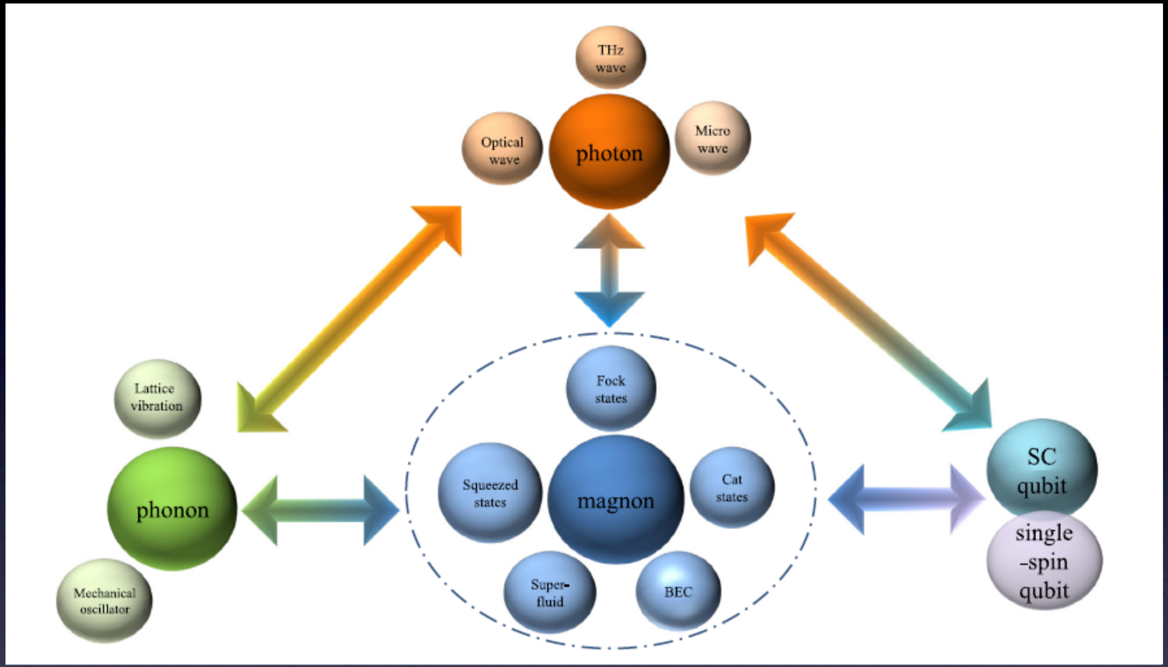


Spin Wave NAND Gate



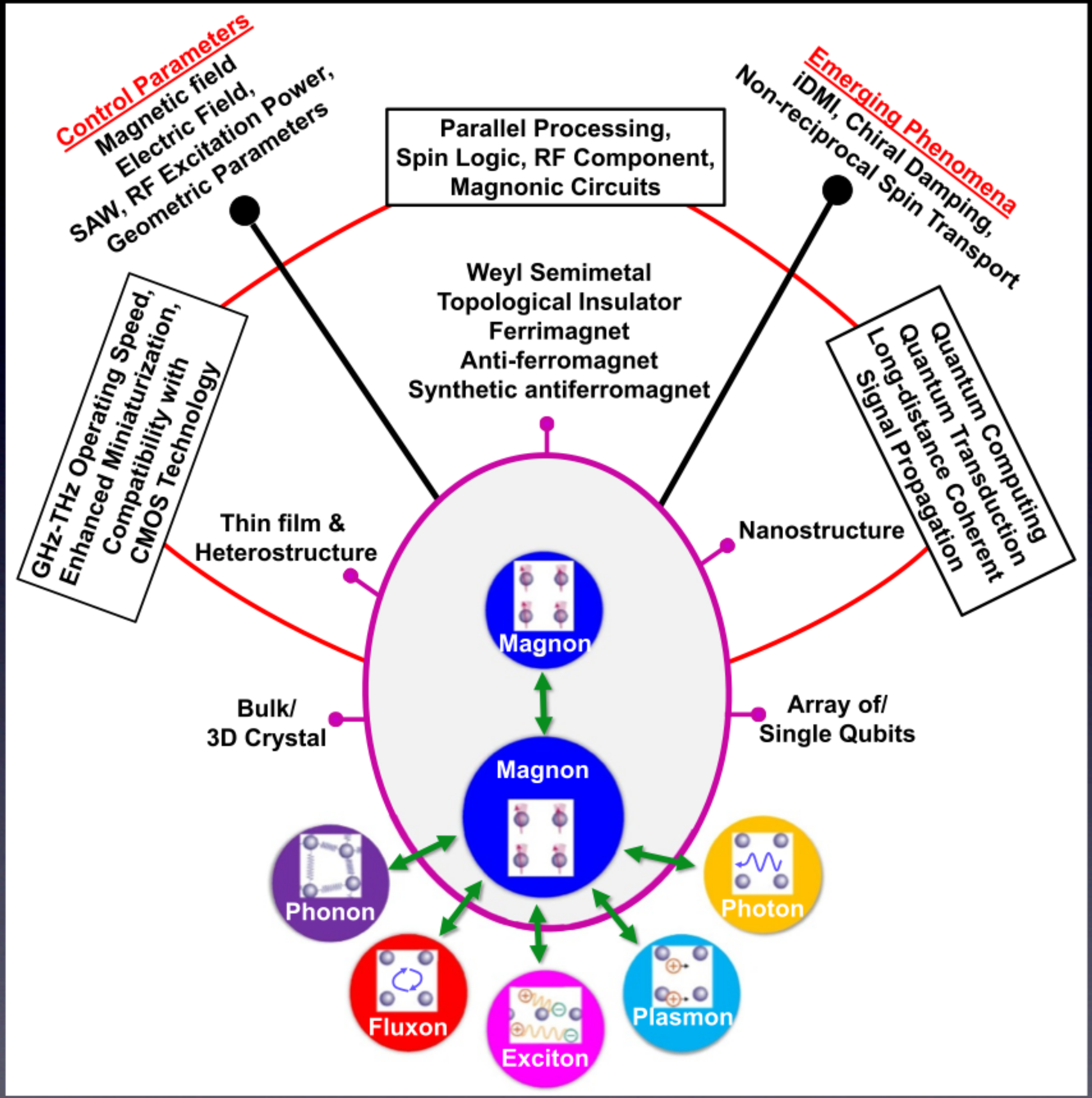
Spin Wave Multiplexer

Magnon Based Hybrid Systems



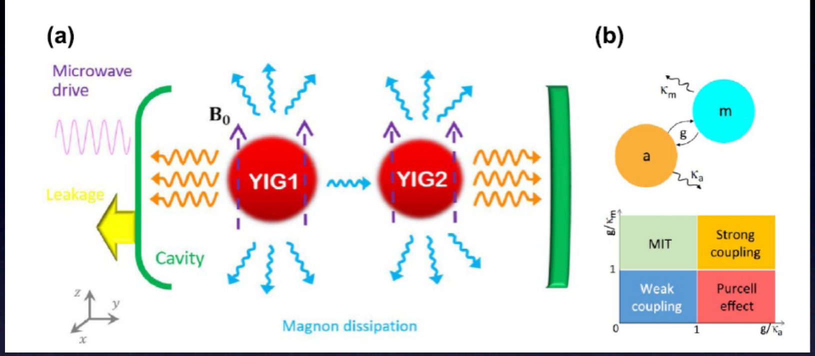
Magnons coupled with other (quasi) particles give rise to a host of interesting device possibilities

Magnon Based Hybrid Systems-Materials & Architectures



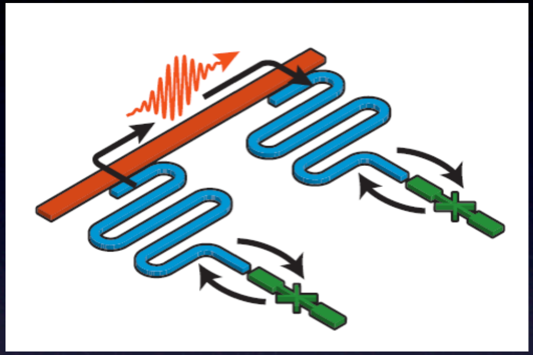
P. K. Pal *et al.* *J. Phys. Condens. Matter* **36**, 441502 (2024)

Other Hybrid Magnon Systems



Phys. Rev. Res. **1**, 023021 (2019)

Magnon-magnon entanglement in a hybrid magnet-cavity system



Appl. Phys. Lett. 123, 130501 (2023)

Unidirectional QST using a non-reciprocal magnetic waveguide

Future Directions: New Magnetothermal effects

Selected for a Viewpoint in *Physics*

PRL **113,** 027601 (2014) PHYSICAL REVIEW LETTERS week ending 11 JULY 2014

Observation of the Spin Peltier Effect for Magnetic Insulators

J. Flipse,[1,*] F. K. Dejene,[1] D. Wagenaar,[1] G. E. W. Bauer,[2,3] J. Ben Youssef,[4] and B. J. van Wees[1]

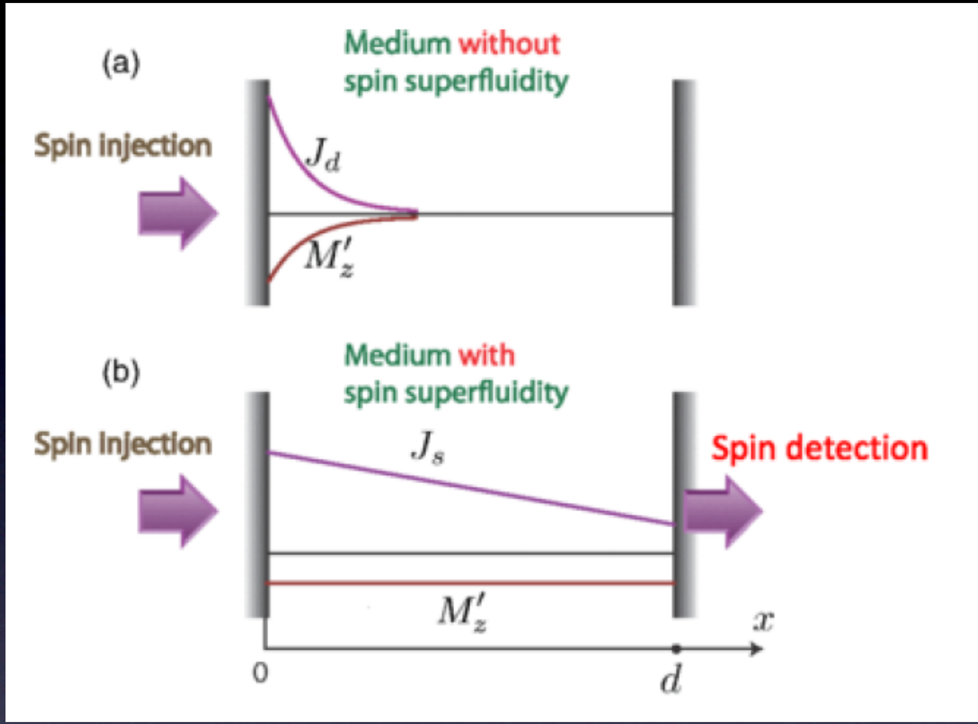
PHYSICAL REVIEW LETTERS **125,** 106601 (2020)

Editors' Suggestion Featured in Physics

Observation of the Magneto-Thomson Effect

Ken-ichi Uchida,[1,2,3,*] Masayuki Murata,[4] Asuka Miura,[1] and Ryo Iguchi[1]

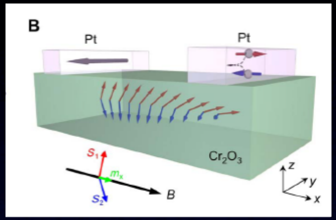
Superfluid Spin Currents

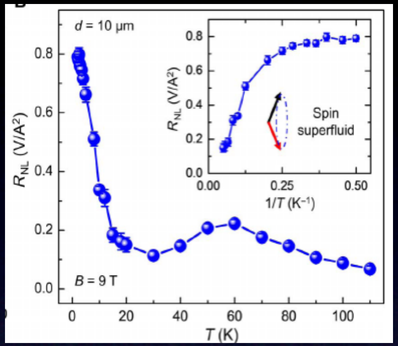


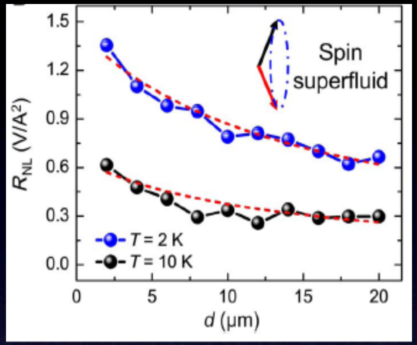
Spin currents are typically diffusive – what if they are superconducting ?

Superfluid spin transport would be a new paradigm in spin transport. Phenomena like Spin Josephson effect now becomes feasible.

Experimental evidence of Spin Superfluidity





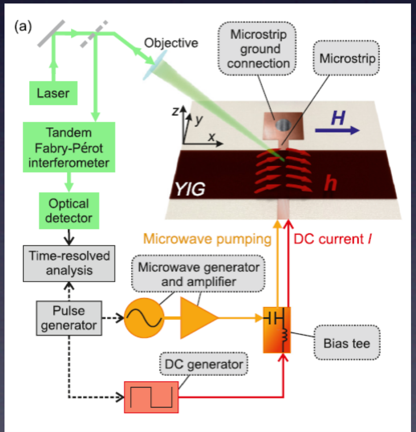


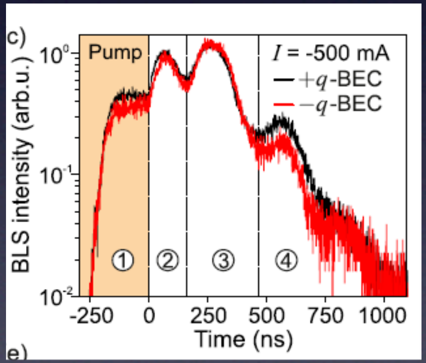
Antiferromagnetic Cr_2O_3

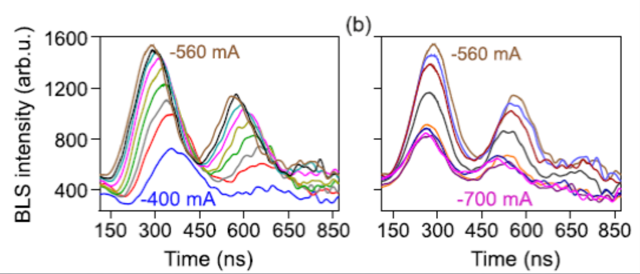
Superfluid state below 20K

Long distance magnon transport

Sci. Adv. 2018; 4 : eaat1098







Phys. Rev. B 104, 144414 (2021)

Ferrimagnetic YIG

BEC of magnons

Josephson Oscillations at 300 K

Summary Part I

Magnons - the quanta of collective spin excitations have distinct properties that make them appealing

Magnons can couple with other quasiparticles / excitations to give rise to a host of device possibilities

Significant progress in the last few years -

Our Spin Caloritronic Set-Up

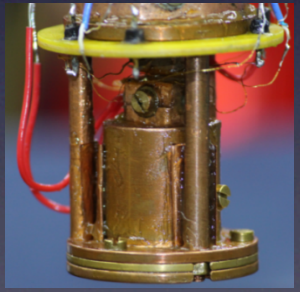
A CCR mated with an electromagnet

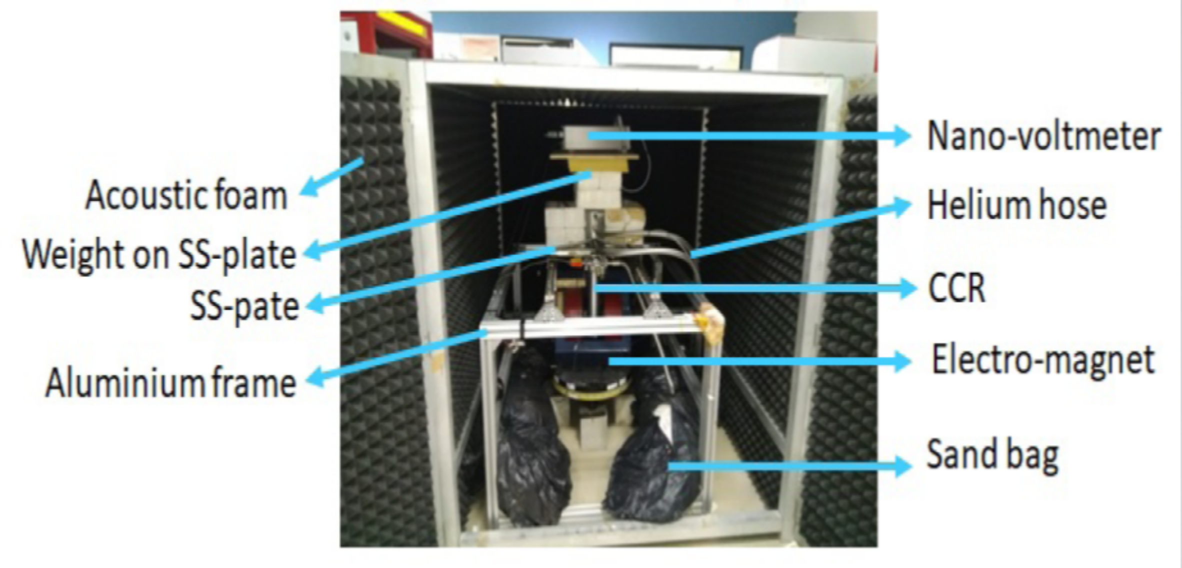
$10\ \mathrm{K} \leq T \leq 300\ \mathrm{K}$

$\nabla T \leq 20\ \mathrm{K}$

$H \leq 2.5\ \mathrm{kOe}$

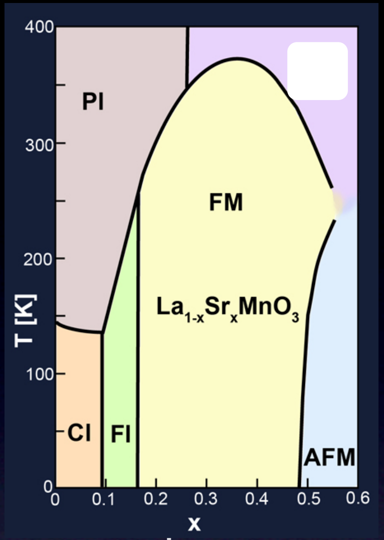
Devices: PLD/crystals + Sputtering

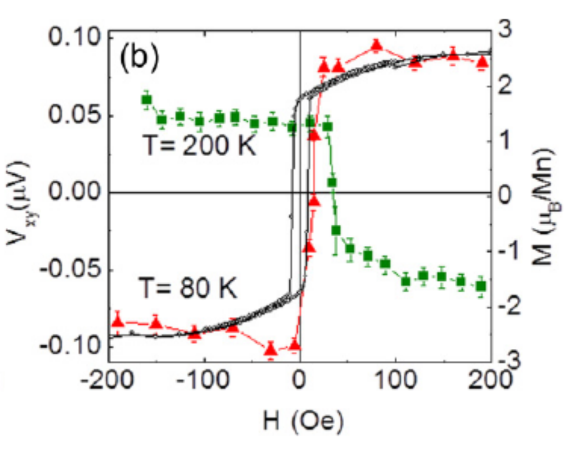




LSSE in mixed valent manganites: the case of LSMO

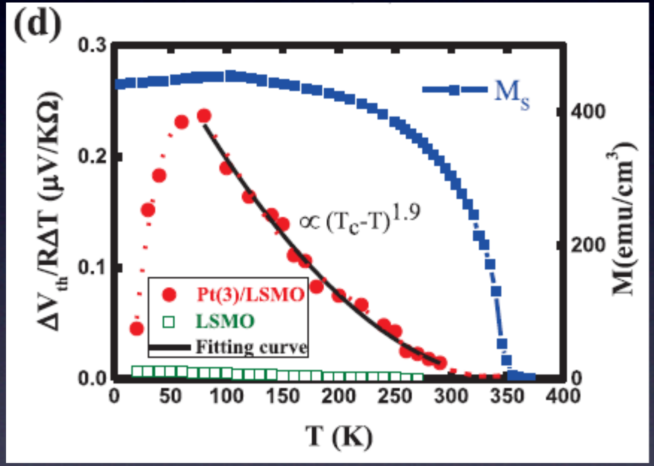
Contradictory reports in literature





C. T. Bui & F. Rivadulla, PRB **90**, 100403(R) (2014)

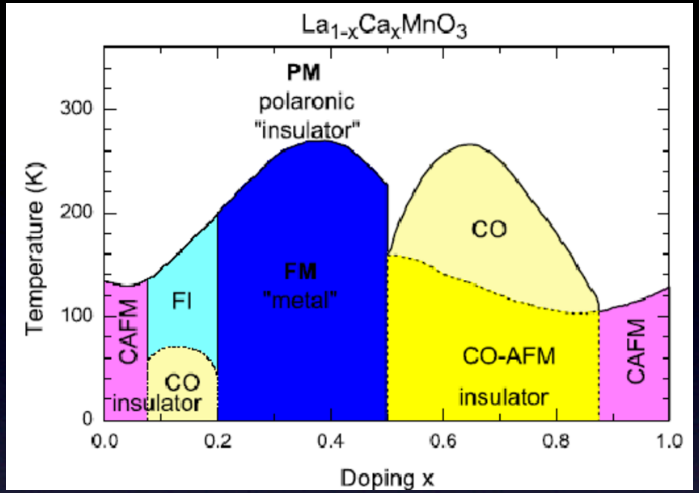
between the intrinsic ANE and SSE signals in LSMO. In our case we have obtained absolutely comparable results using either Pt or Au (see the Supplemental Material, Fig. S5 [21]). Therefore, with our resolution limit we could not detect a signal compatible with SSE in LSMO.

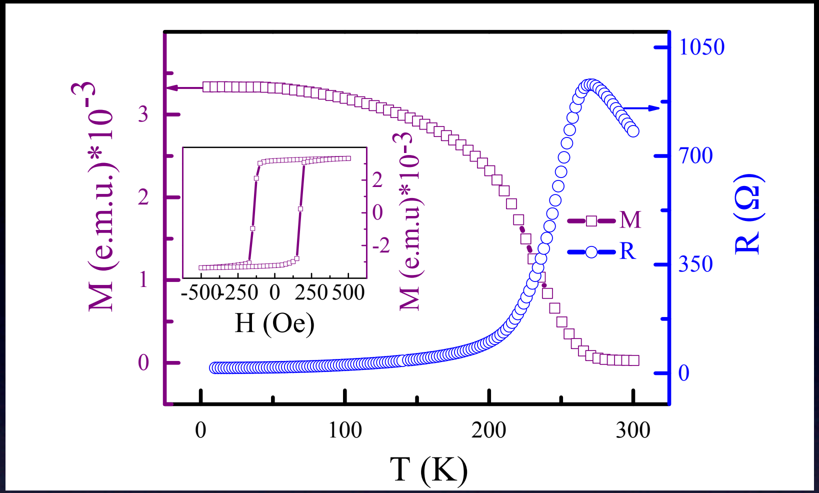


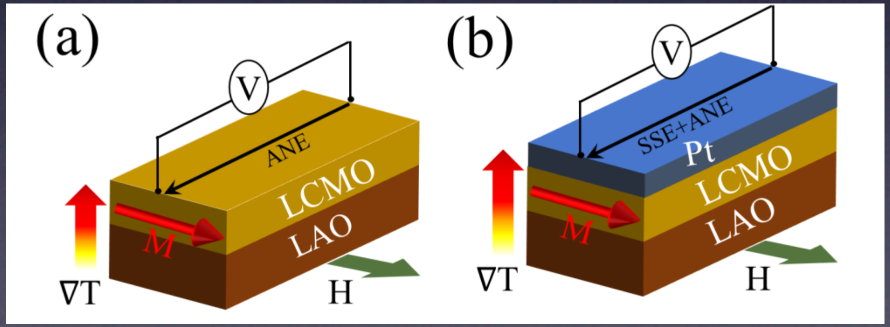
B. W. Wu *et al.*, PRB **96**, 060402(R) (2017)

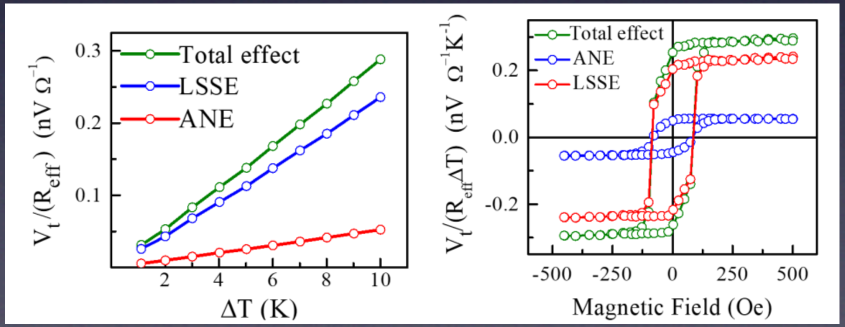
a negative spin Hall angle. Unlike Py and CFB in which the ANE dominates the transverse thermal transport, more than 95% of the thermal voltage comes from the LSSE in LSMO. The nontrivial behavior of the temperature depen-

LSSE in $La_{0.7}Ca_{0.3}MnO_3$/Pt

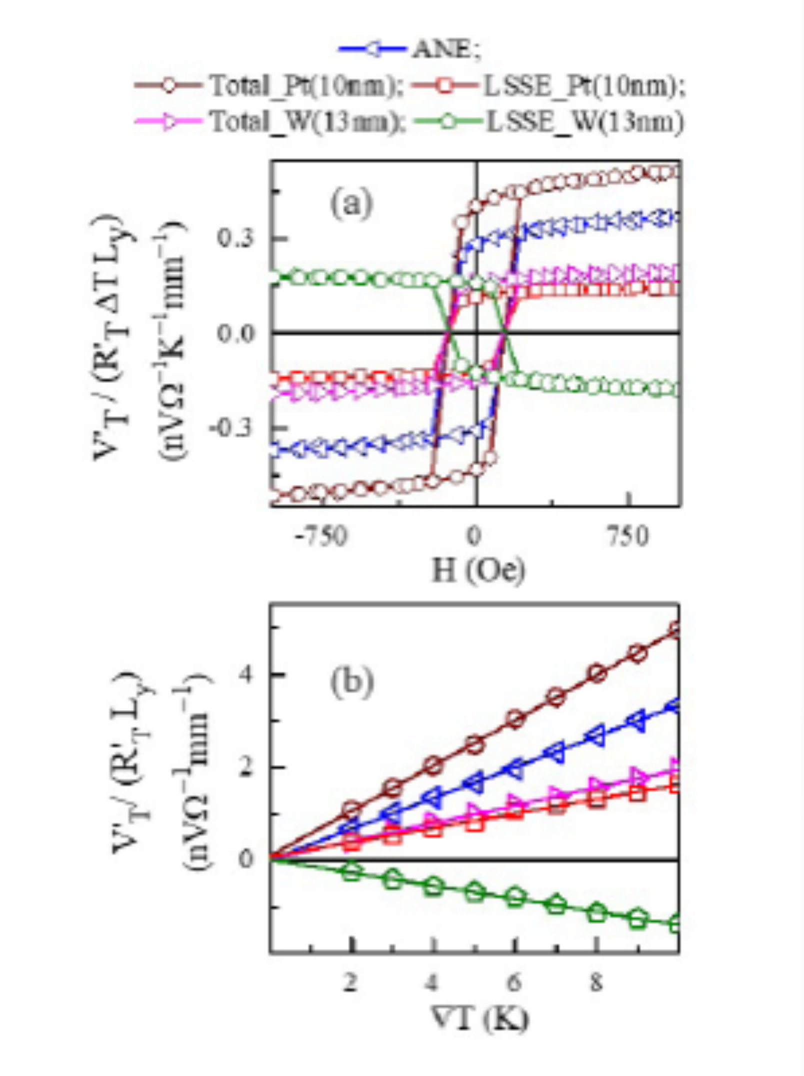


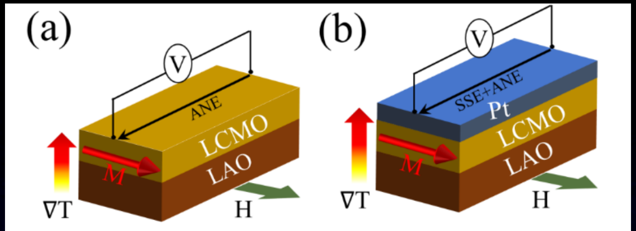






LSSE in LCMO/Pt – role of the 'conversion' layer

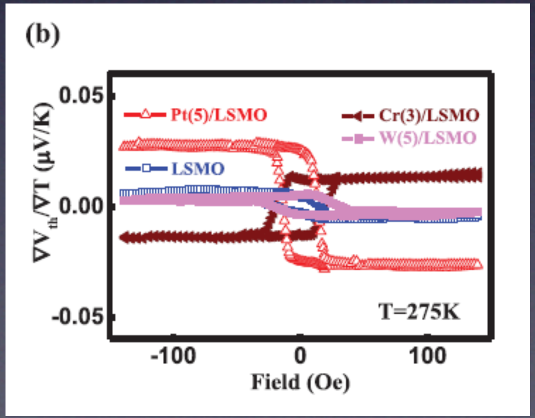




$$V_{ISHE} = (\theta SH\ \rho)\ Js \times \sigma$$

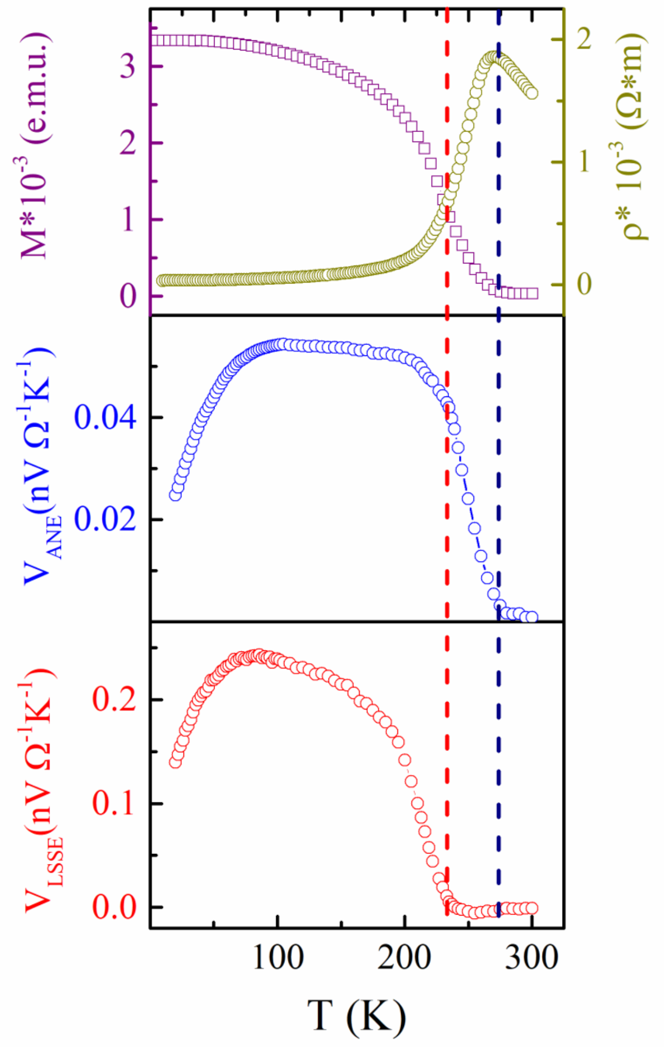
Pt and W have opposite signs of θ_{SH}

The V_{LSSE} ***has*** to invert !



B. W. Wu *et al.*, PRB **96**, 060402(R) (2017)

T dependent LSSE in $La_{0.7}Ca_{0.3}MnO_3$/Pt



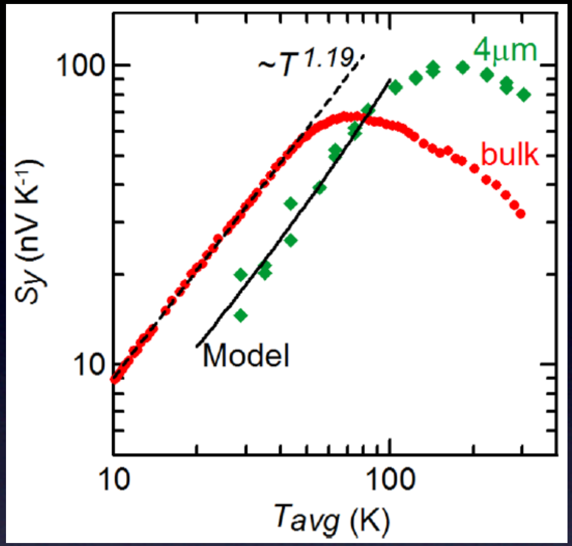
LSSE and ANE have different *T* dependences

ANE is tied with ρ(*T*)
SSE rises at lower *T*

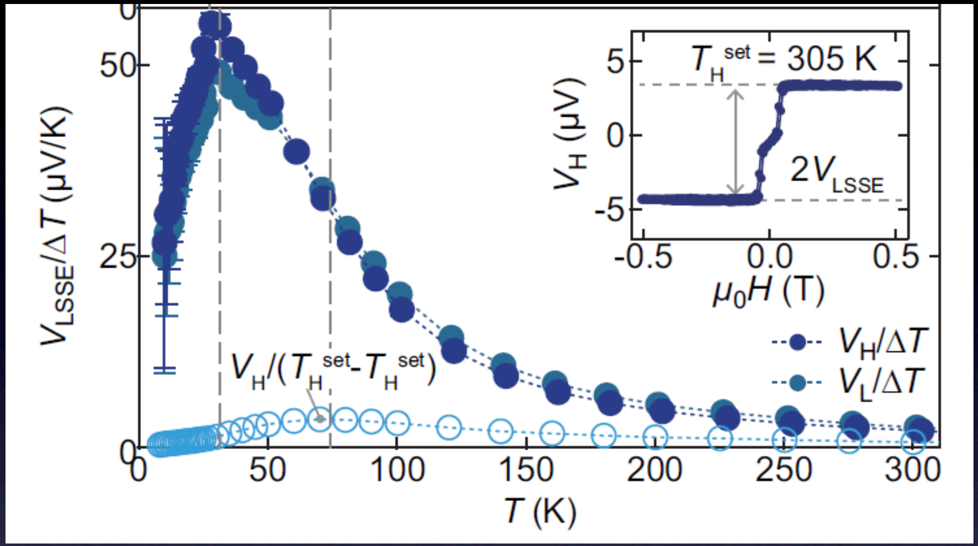
$V_{LSSE}(T)$ exhibits a peak ~ 85K
interplay between the magnon population & lifetimes

seen in most *T* dependent LSSE measurements

LSSE in the low T regime



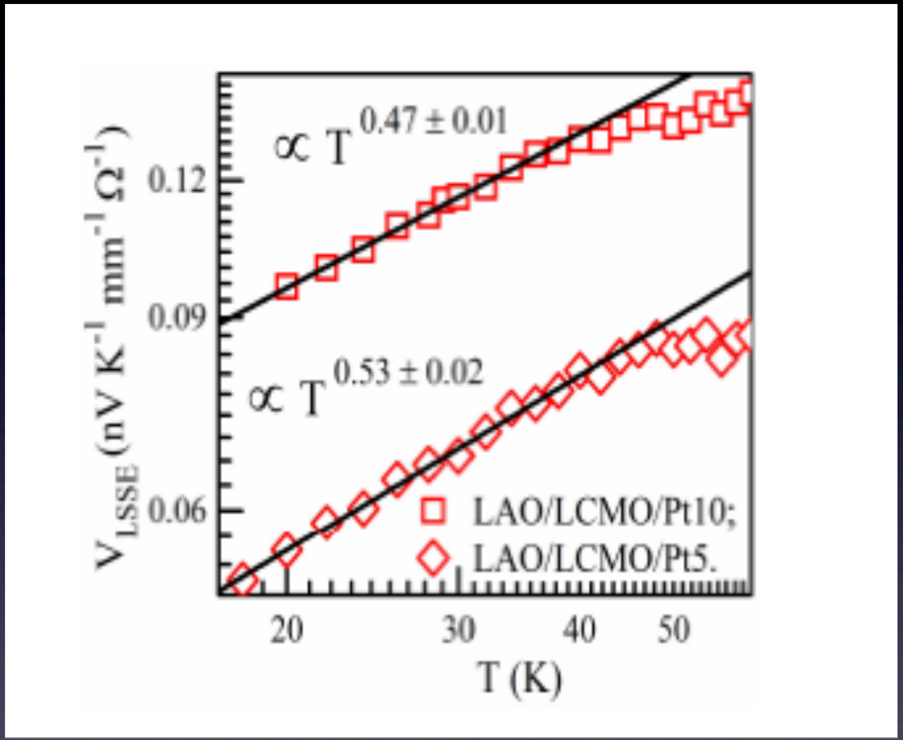
PRB **92**, 054436 (2015)



PRB **95**, 174401 (2017)

Pseudo- linear low T region (varying from 0.8 to 1.2)

LSSE in the low T regime



PRL **124**, 017203 (2020)

Magnon Spin current theory

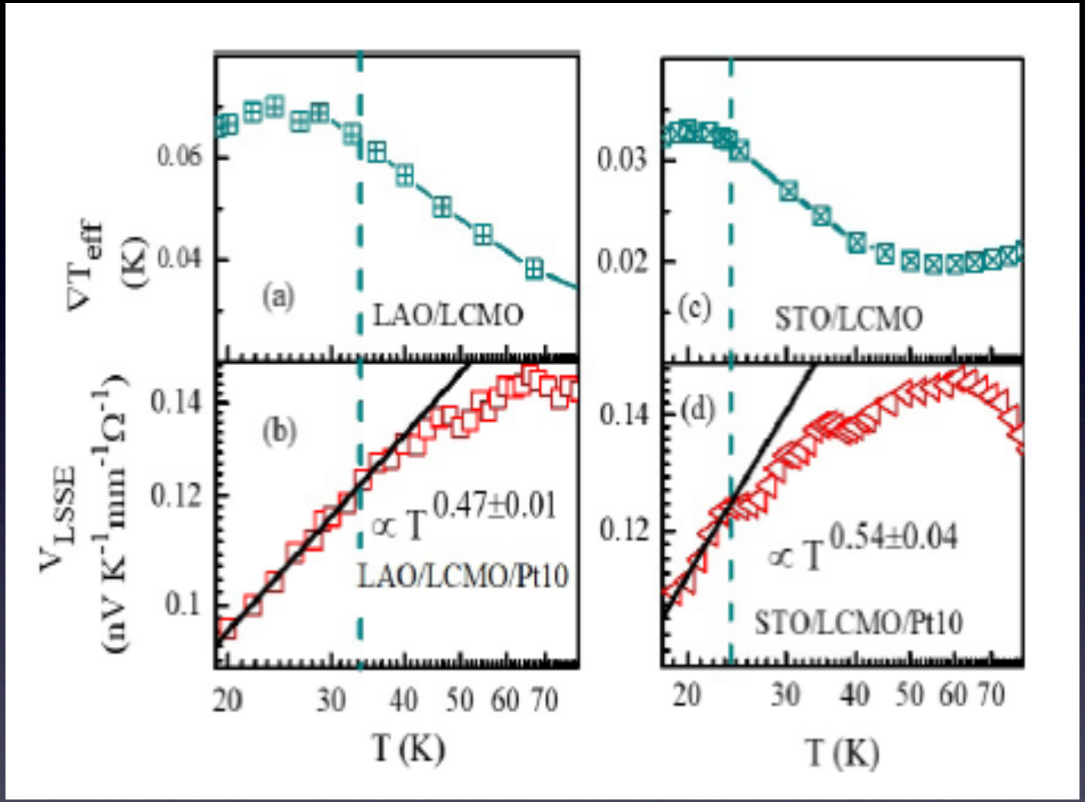
PRB 81, 214418 (2010)
PRB 89, 014416 (2014)

$$V = \rho_N \omega \lambda_N \frac{2e}{\hbar} \theta_{SH} \tanh \frac{t_N}{2\lambda_N} {J_S}^2(0)$$

$${J_S}^2(0) = \frac{(k_B T)^2 (3\tau_S L \tau_m)^2}{4\pi M D 6\pi^2 \hbar} (\frac{C_{3/2}}{C_{1/2}})^{1/2} C_{5/2} g^{\uparrow\downarrow} k_B \Delta T$$

$$V \propto T^{0.5}$$

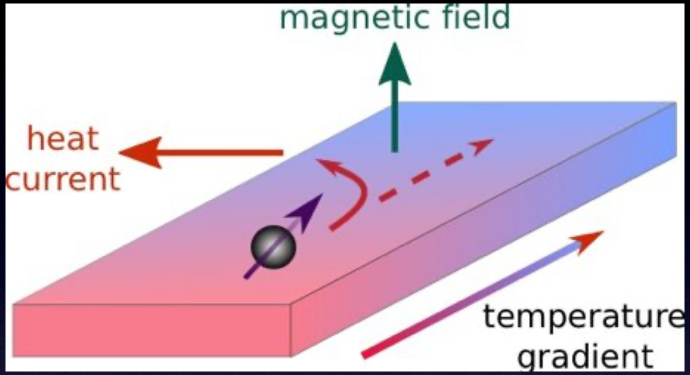
LSSE in the low *T* regime- the role of the substrate



The effective temperature gradient is important

PRL **124**, 017203 (2020)

The Thermal Hall Effect



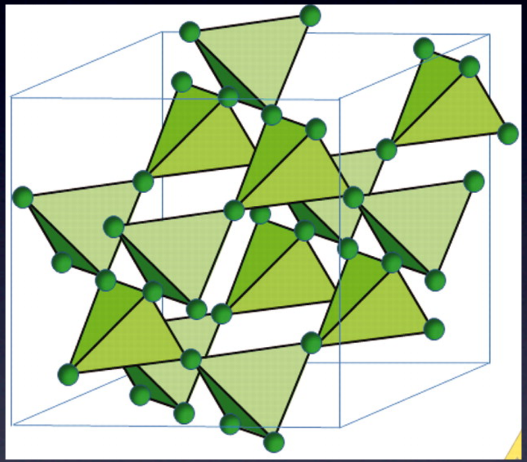
The Righi-Leduc effect

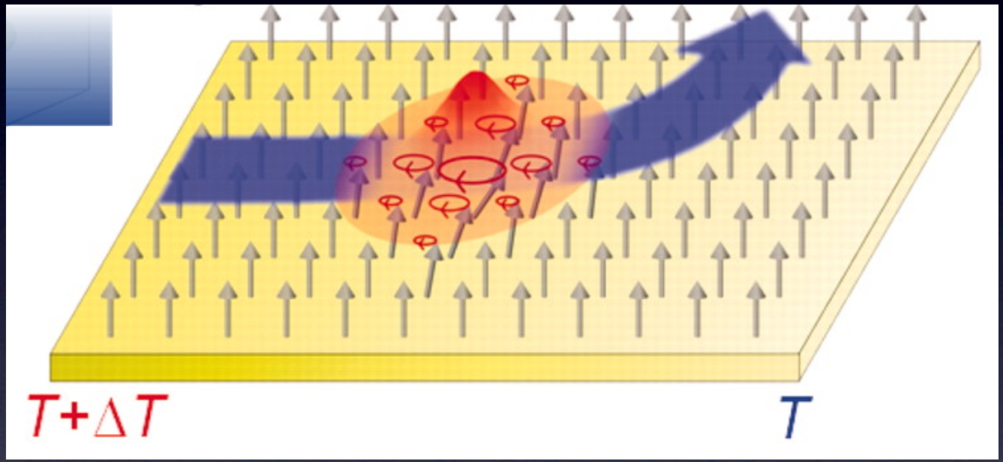
Thermal analogue of the Hall effect

Reported in Semiconductors [JAP **32**, 2257 (1961)]

and metals [Proc. R. Soc. Lond. **A293**, 275 (1966)]

The observation of the Magnon Hall Effect

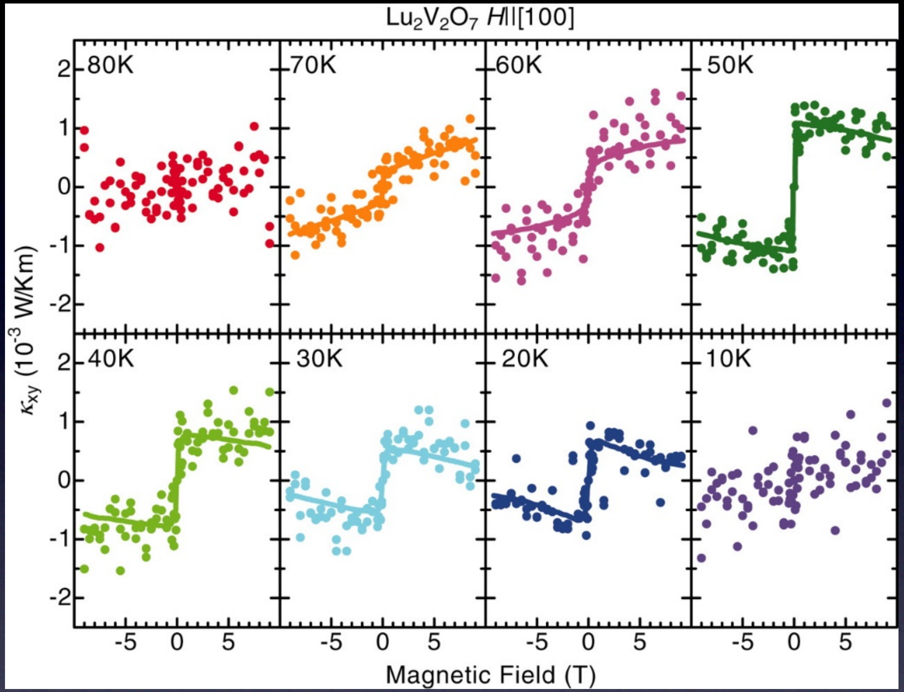


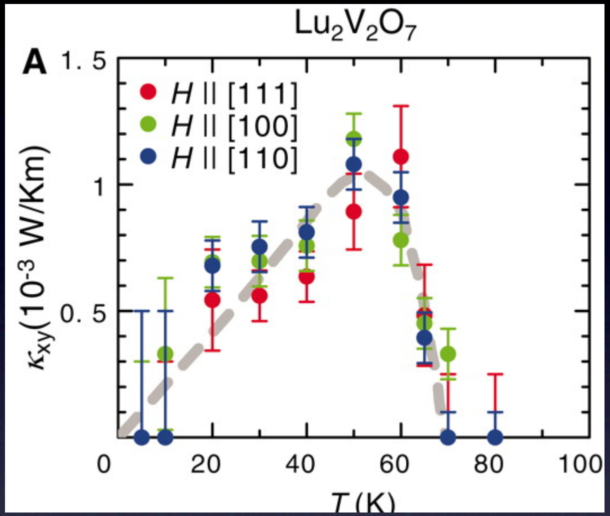


Y. Onose et. al., Science **329**, 297 (2010)

In $Lu_2V_2O_7$, the Dzyaloshinskii-Moriya interaction plays the role of a vector potential, giving rise to the magnon Hall effect.

The observation of the Magnon Hall Effect





Y. Onose et. al., Science **329**, 297 (2010)

Measured using on-specimen chip thermometers

The role of Magnon topology

PHYSICAL REVIEW B **90**, 024412 (2014)

Edge states in topological magnon insulators

Alexander Mook,[1] Jürgen Henk,[2] and Ingrid Mertig[1,2]
[1]*Max-Planck-Institut für Mikrostrukturphysik, D-06120 Halle (Saale), Germany*
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(Received 15 May 2014; revised manuscript received 27 June 2014; published 18 July 2014)

PRL **117,** 157204 (2016) PHYSICAL REVIEW LETTERS week ending 7 OCTOBER 2016

Tunable Magnon Weyl Points in Ferromagnetic Pyrochlores

Alexander Mook,[1] Jürgen Henk,[2] and Ingrid Mertig[1,2]
[1]*Max-Planck-Institut für Mikrostrukturphysik, D-06120 Halle (Saale), Germany*
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(Received 25 June 2016; revised manuscript received 17 August 2016; published 7 October 2016)

These ferromagnetic pyrochlores are thought to be ideal test beds to look for manifestations of the magnon toplogy – akin to that seen in topological electronic systems

On accessing the Magnon topology

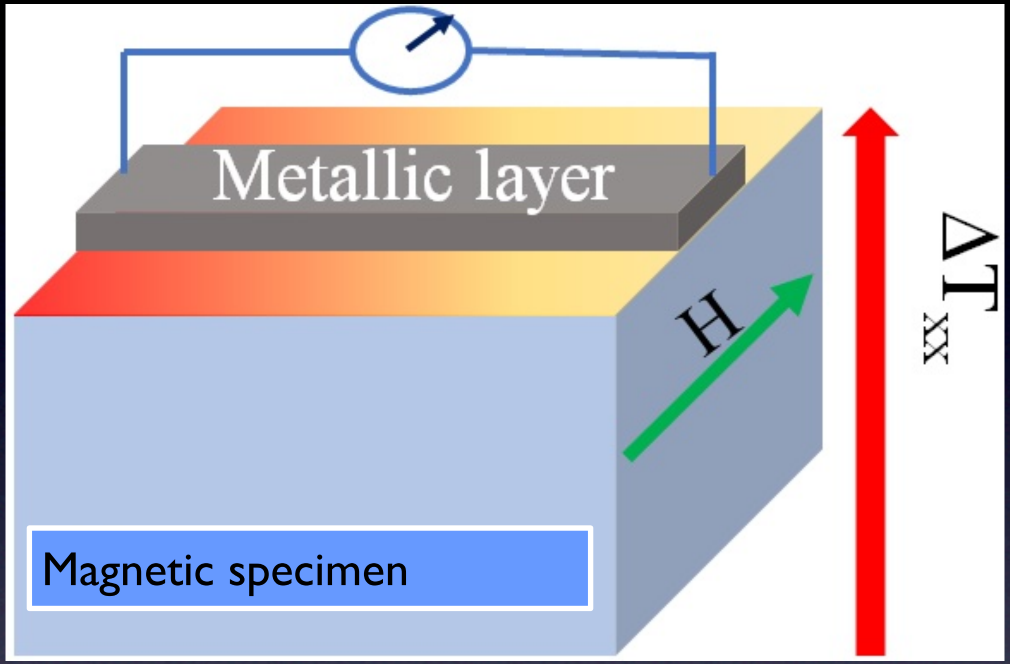
- Detailed magnon bandstructure calculations suggest topologically protected magnon surface states in this family of pyrochlores – ***provided H is not along [100]***

- However, no 'direct' experimental verification so far

- Traditional tools of looking at magnon band-structure might not be suitable

- This is in contrast to electronic systems – ARPES, STS, transport, etc

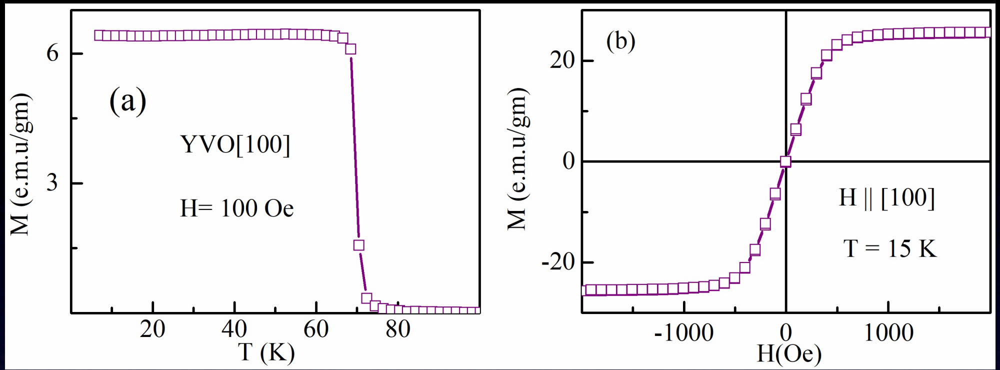
Can the SSE geometry be used for MHE measurements ?

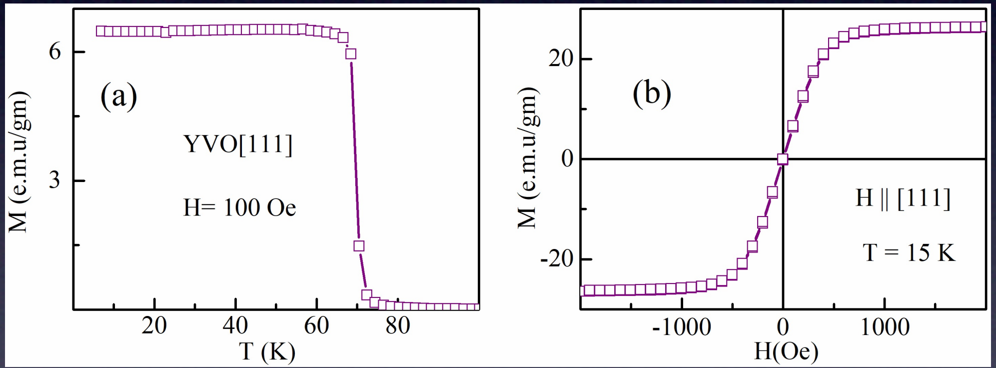


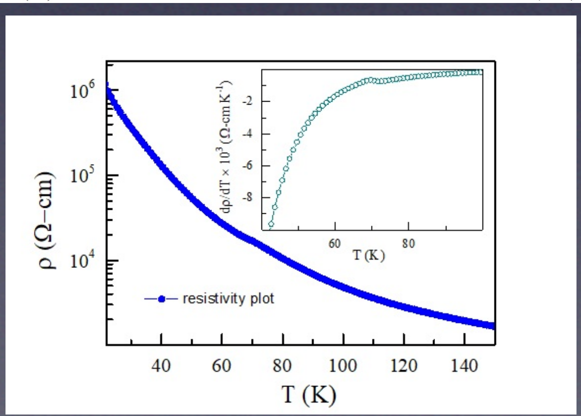
Measuring the Seebeck response of the metallic layer should give us a measure of the Magnon Hall Effect

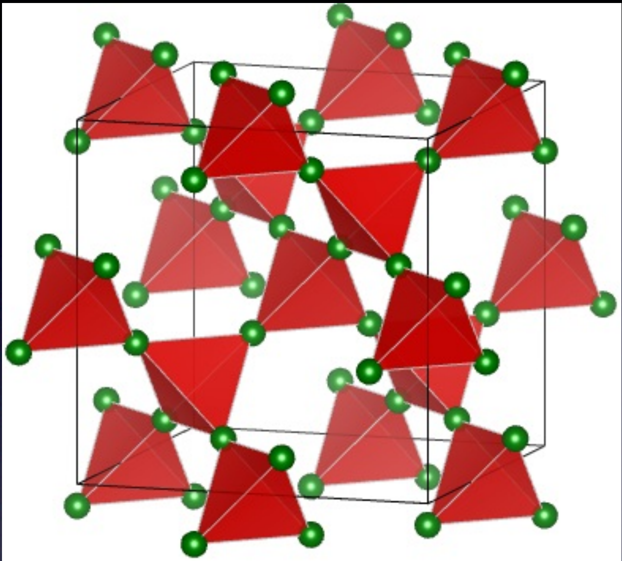
An electrical means of measuring MHE ?
More sensitive to surface phenomena ?

Our system – the closely related $Y_2V_2O_7$

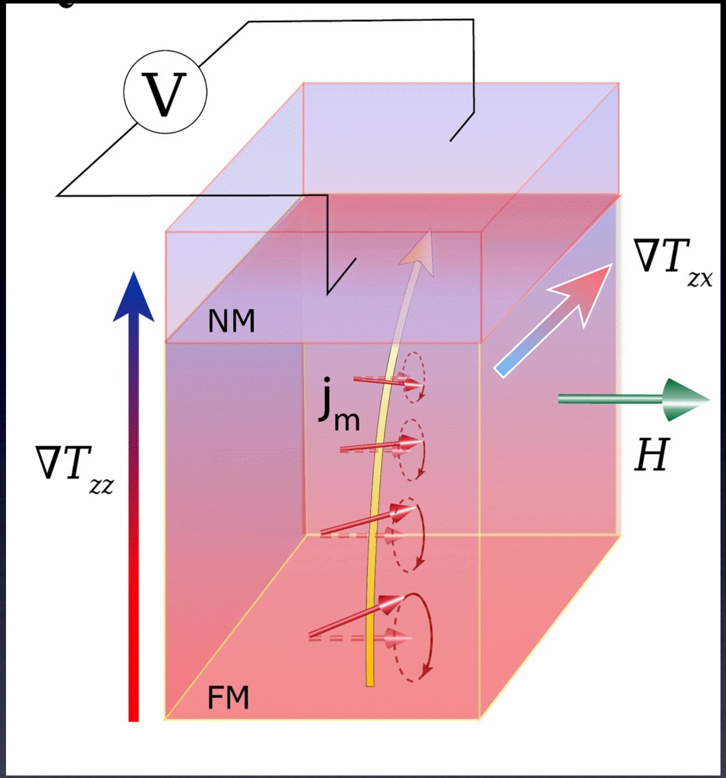




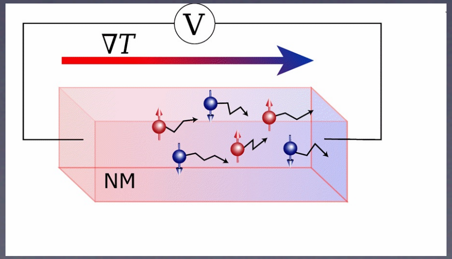


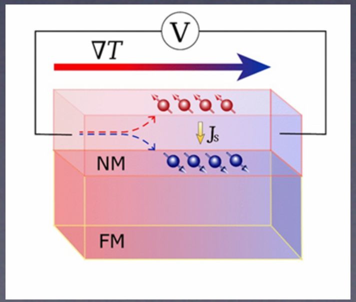


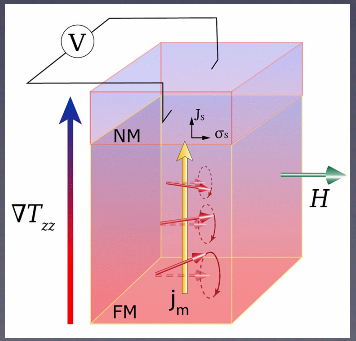
The measured signal



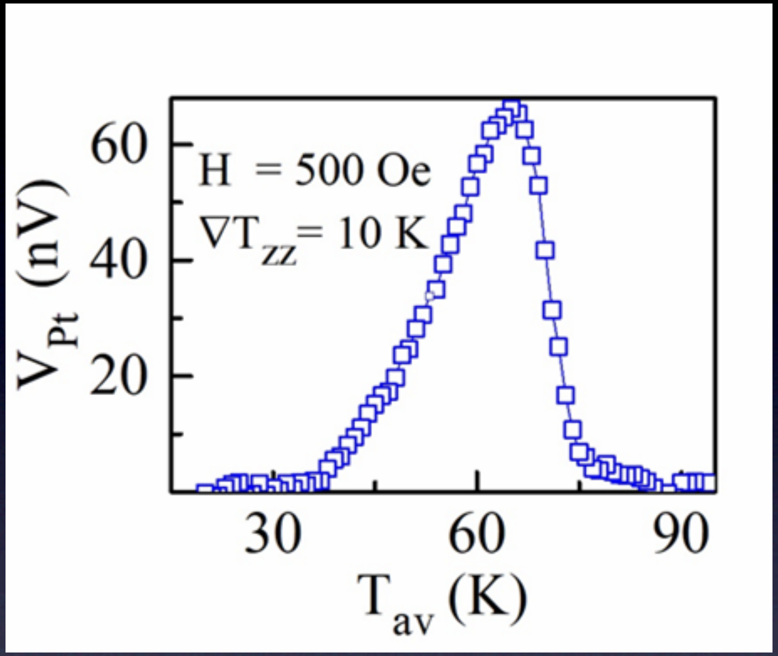
$$V = \left[S + \Delta S_1 + \Delta S_2(1 - m_y^2)\right] \nabla T_{zx} + V_{LSSE}(T)$$

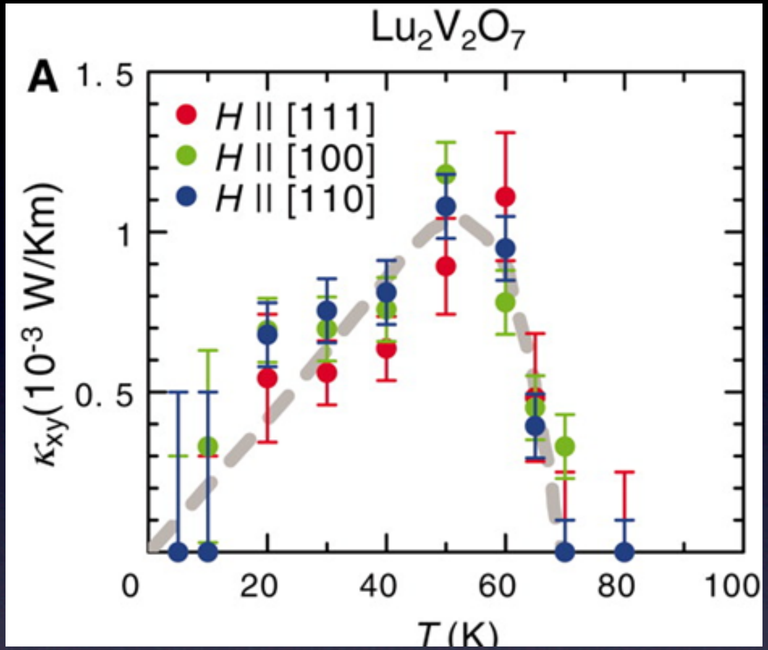






The measured signal with H || [100]

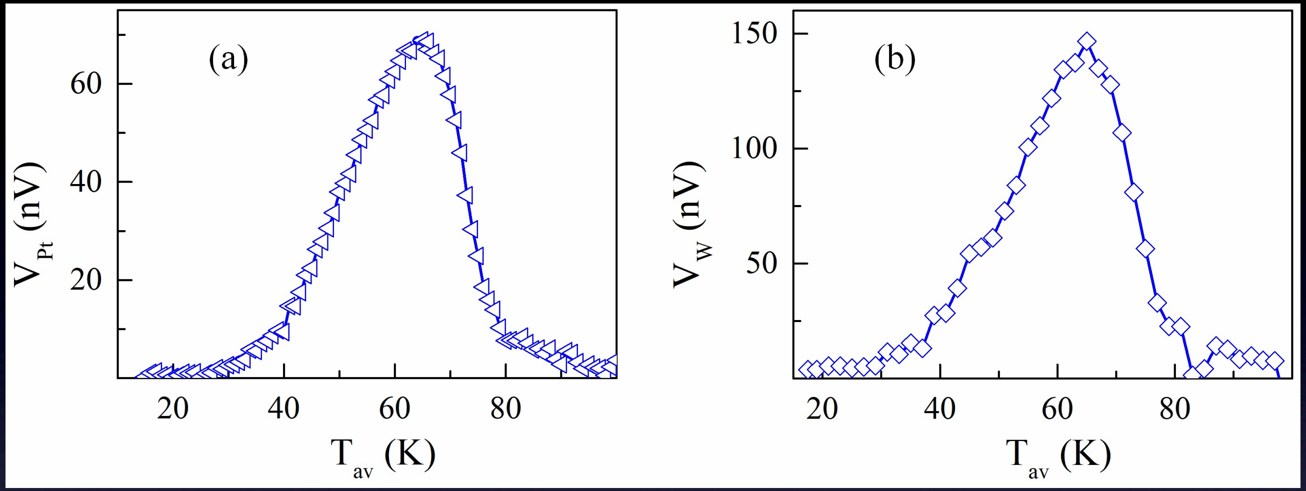


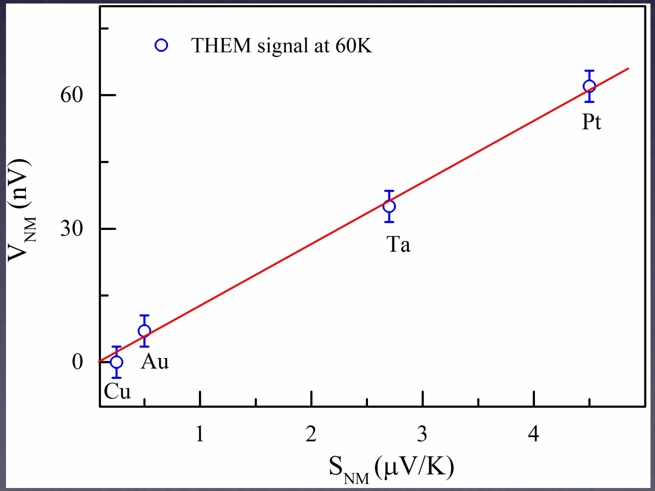


Y. Onose et. al., Science **329**, 297 (2010)

The measured voltage follows the expected MHE !

The measured signal with different metal layers

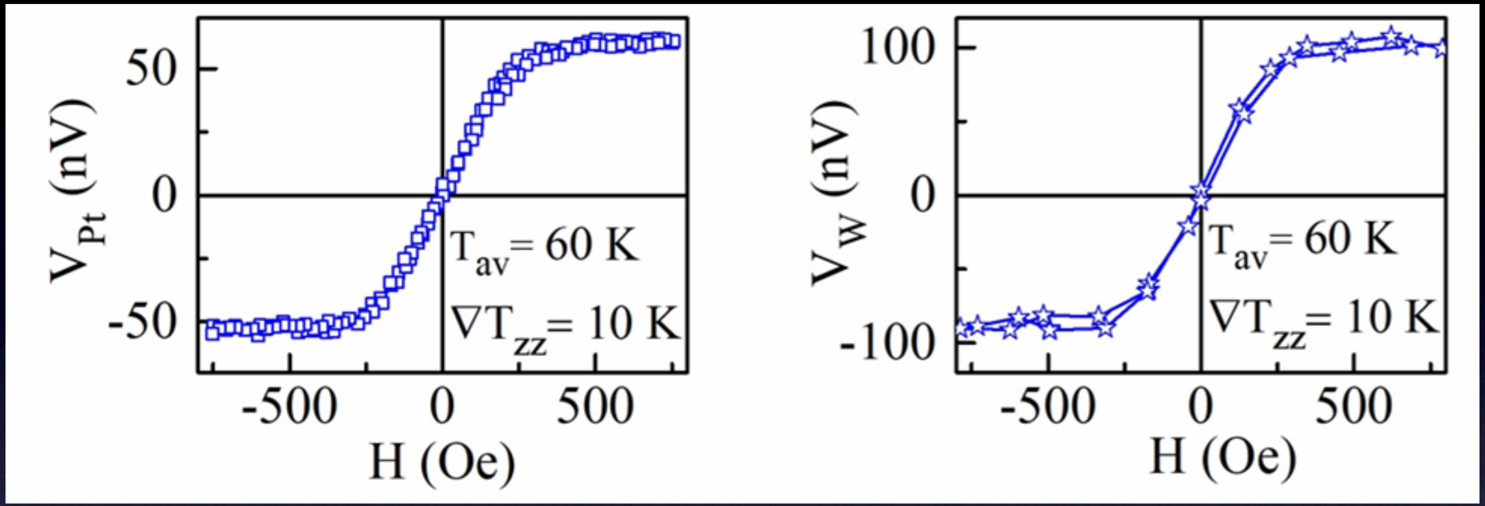




Pt and W have the same polarity – LSSE can be ruled out

The measured voltage scales with the Seebeck co-efficient of the NM layer

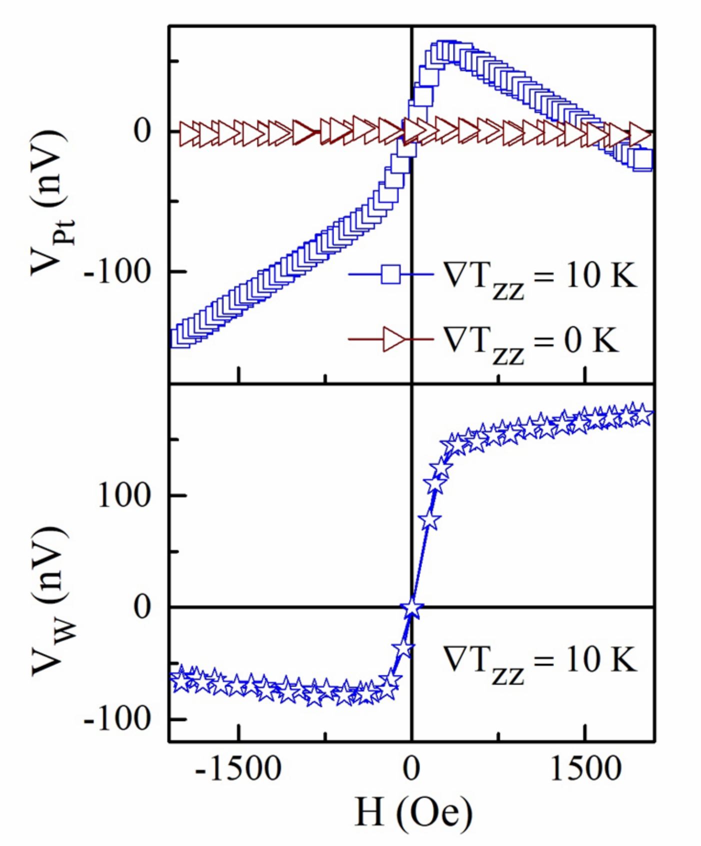
The measured signal with H || [100]

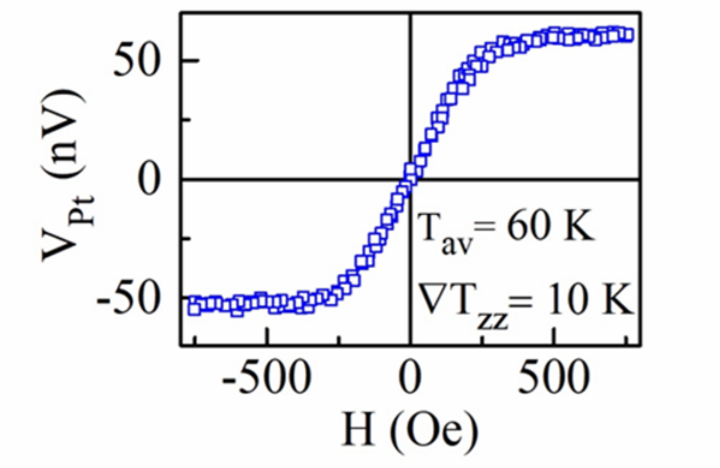


The field dependence is similar with Pt and W layers

Reconfirming again that the LSSE contribution is ruled out

The measured signal with H || [111]

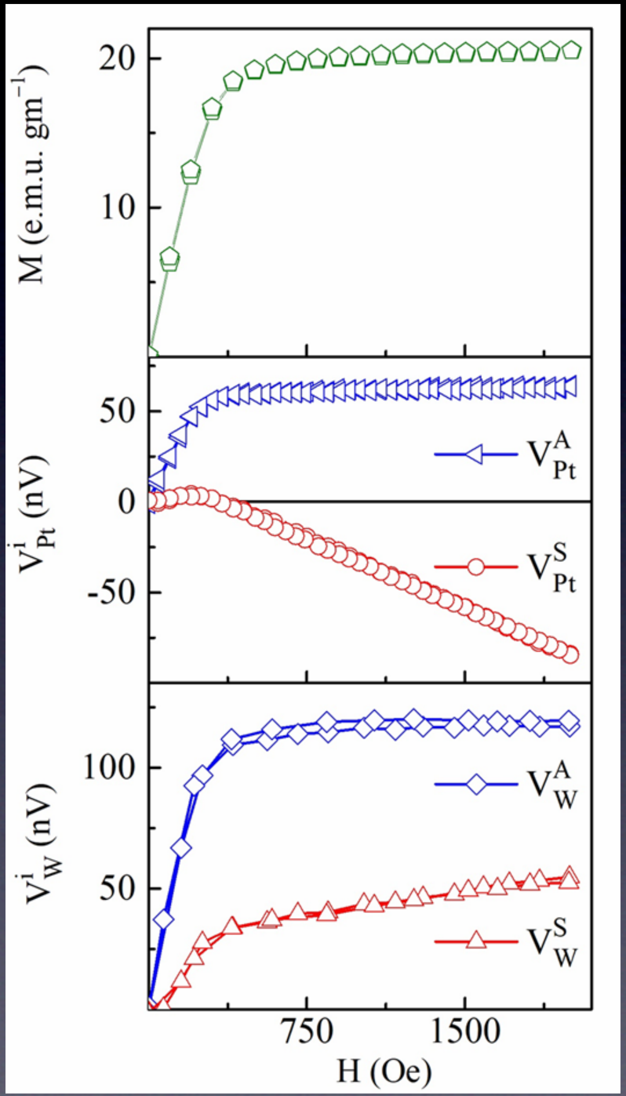




H || [100]

The measured voltage looks different to that measured in the H||[100] configuration

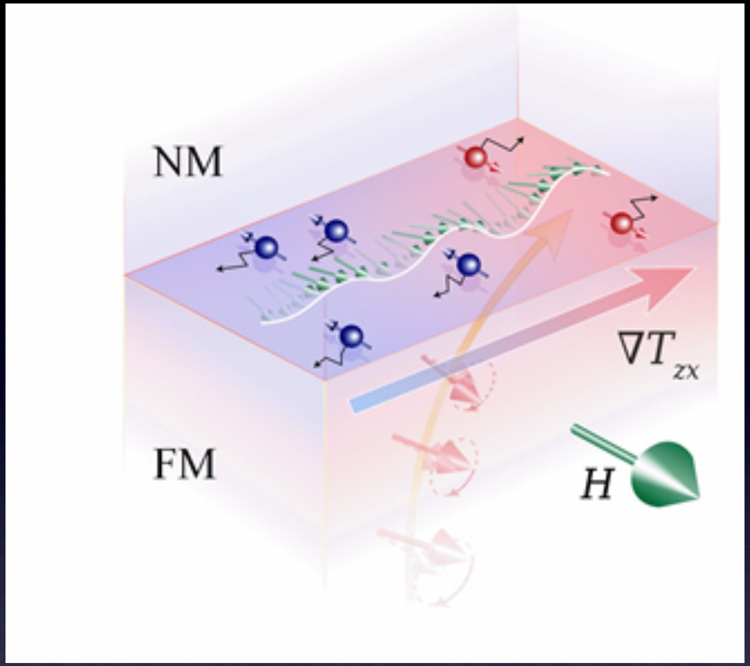
<u>An additional symmetric component when H || [111]</u>



The antisymmetric component is similar to M

An additional symmetric component – <u>only along the H||[111] direction</u>

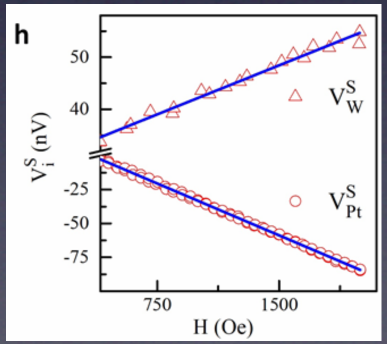
Why do we see this additional voltage ?



An interfacial magnon drag contribution

Magnons at the surface of the FM drag electrons in the adjacent NM layer

Interfacial Drag phenomena		
Phonon	Electron	Known
Phonon	Magnon	Known
Magnon	Magnon	Known
Magnon	Electron	This work



$V^S \propto \alpha\, \eta\, P_s\, H + constant$

P_S = spin polarization at the interface driven by the SNE

The Spin Nernst angle has different signs in Pt and W !

Physical Review B **111**, 054435 (2025)

Patent: IN202221043561

Summary Part II

- ➢ Disentangling ANE and SSE in LCMO/Pt - perfect match with theory
- ➢ Using the LSSE device geometry for measuring the magnon Hall Effect
    - An additional contribution from the interfacial magnon drag
    - An electrical means of inferring on magnon surface states


Dr. Avirup De


Anna Francis


Dr. D. Prabhakaran


Prof. Satish Ogale


Dr. Guru Venkat

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