Magnon heat conduction and spin-Seebeck effect in helimagnetic Cu_2OSeO_3

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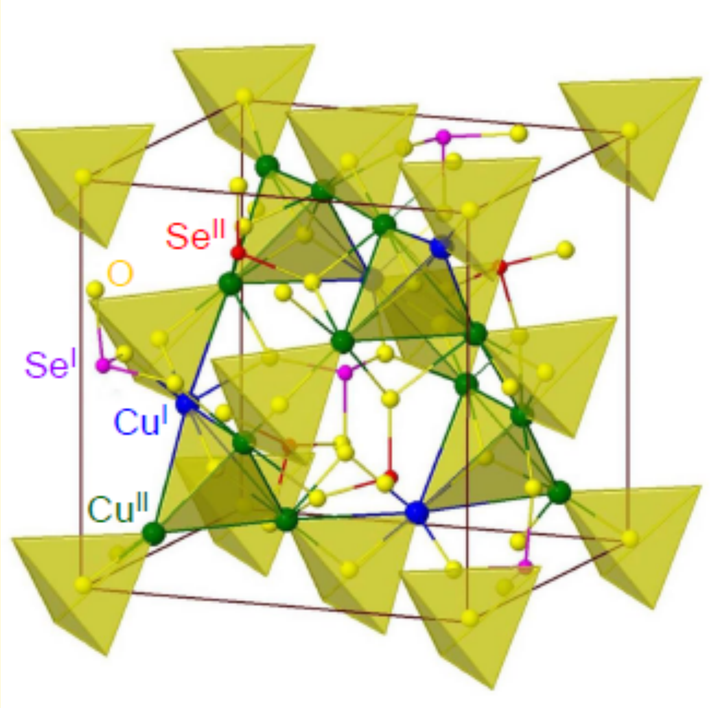
Cu_2OSeO_3 : Spin structure and phases



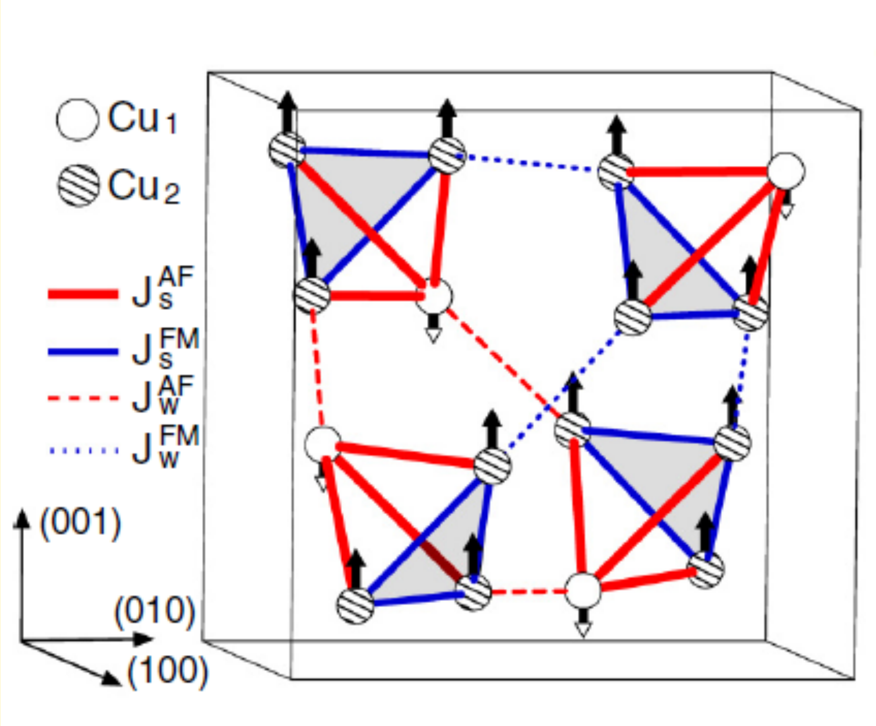
Cubic, noncentrosymmetric

P$2_1$3, a=8.925 Å (8 f.u.)

Weak antisymmetric exchange (D-M) interactions cause long-range canting of spins

$T_C \approx 58$K

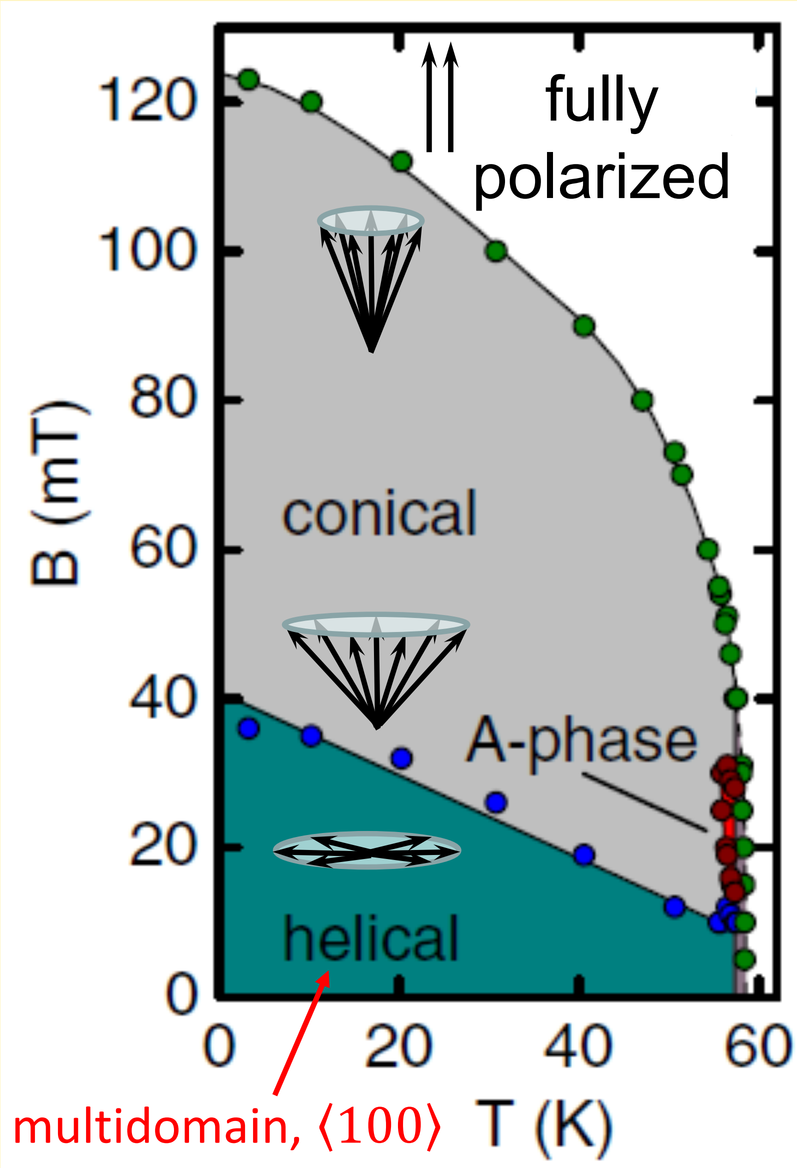
J. Romhányi et al., PRB **90**, 140404(R) (2014)



fcc lattice of Cu_4 tetrahedra (S=1)

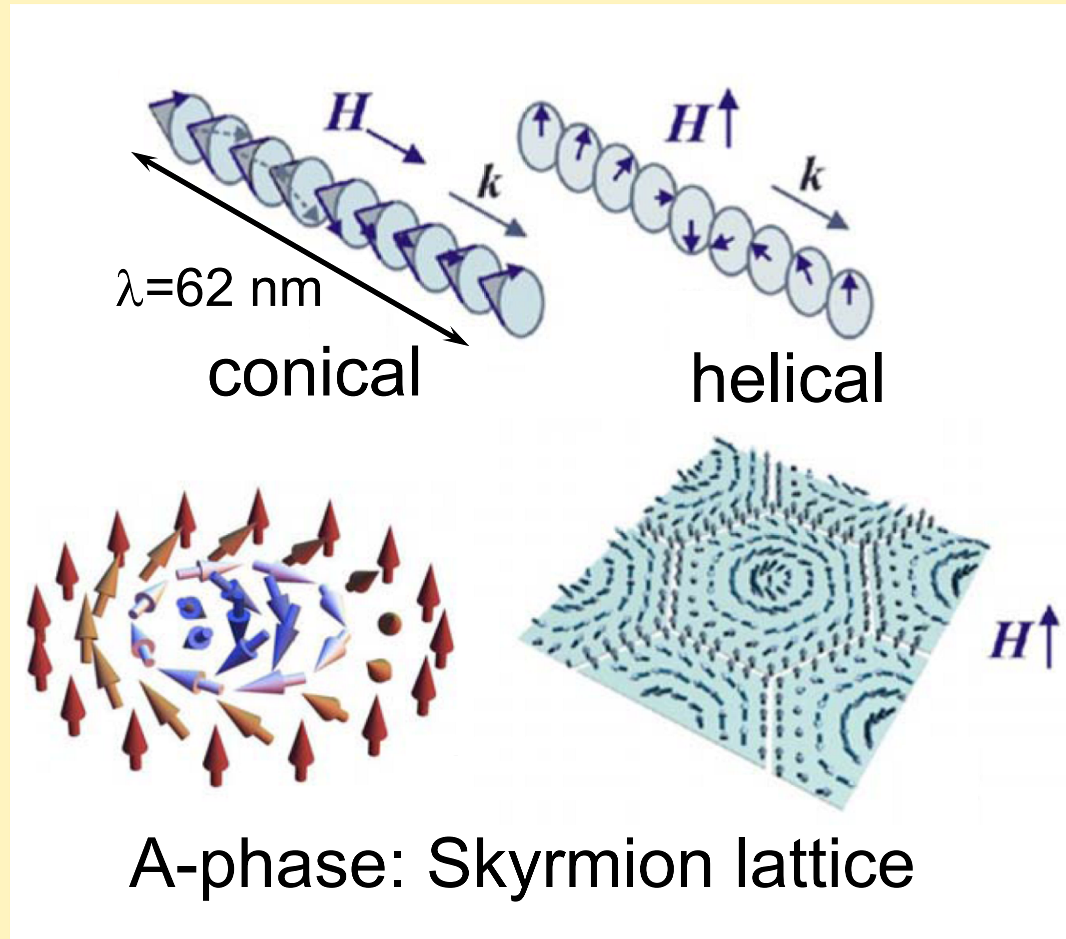
("3 up-1 down")

Cu_2OSeO_3 : Spin structure and phases



T. Adams *et al.*, PRL **108**, 237204 (2012)

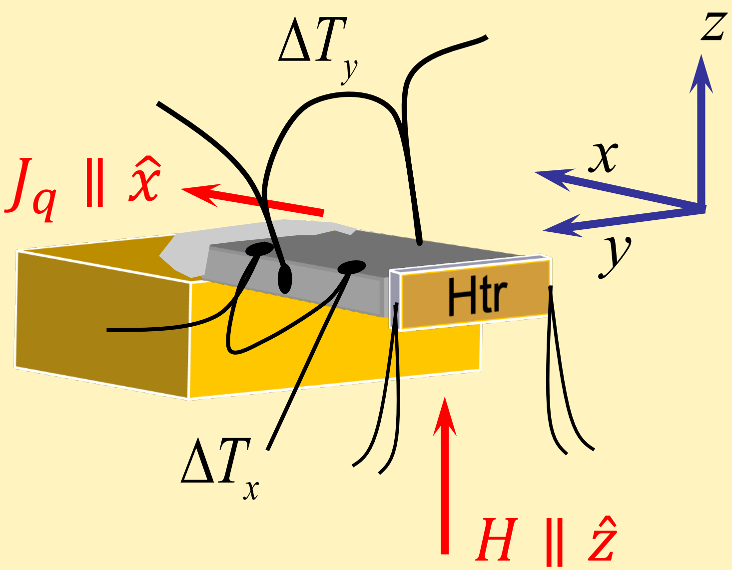
Long-range spin textures



M. Baenitz *et al.*, Max Planck Inst. For Chem. Phys. Sol.

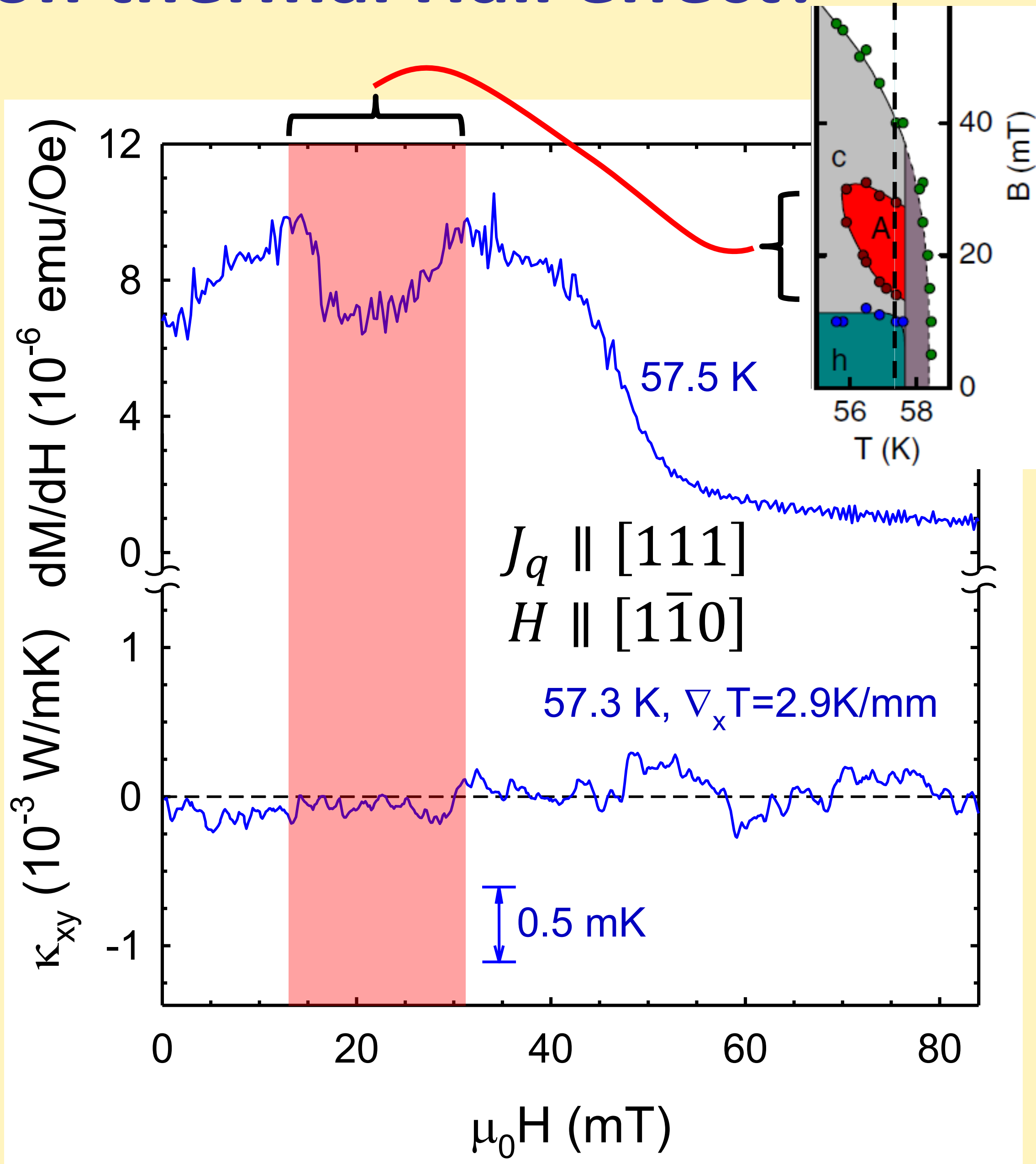
Other chiral magnets: MnSi, FeGe,…

Cu_2OSeO_3 : Skyrmion thermal Hall effect?



$$\kappa_{xy} = \kappa_{yy} \frac{\nabla_y T}{\nabla_x T}$$

$$\cdots\ \kappa_{xy} < 10^{-4}\ \mathrm{W/mK}$$

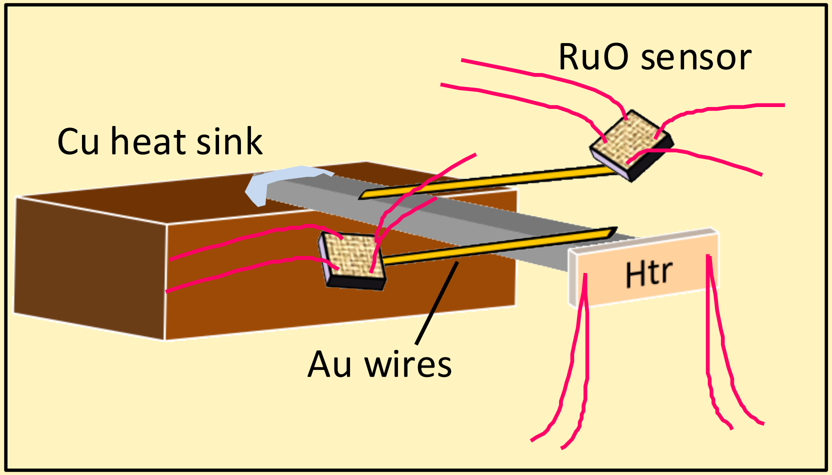


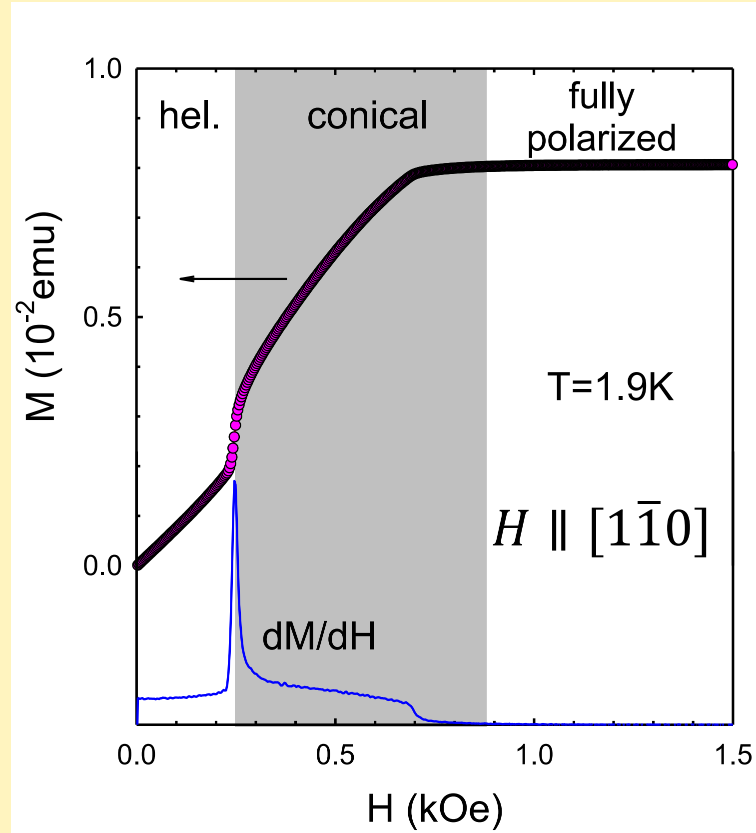
Steady-state measurements, low-T

Single-crystal Cu_2OSeO_3 growth by vapor transport method (Johns Hopkins)

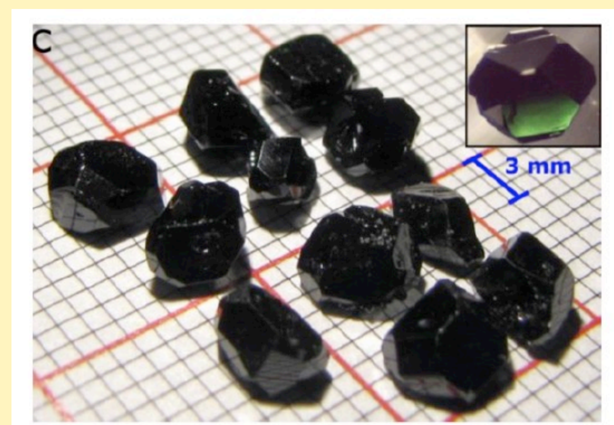
Typical specimen size: $0.2 \times 0.2 \times 3.5\ mm^3$

$$\ell_0 = 2\sqrt{A/\pi} = 0.15 - 0.60mm$$

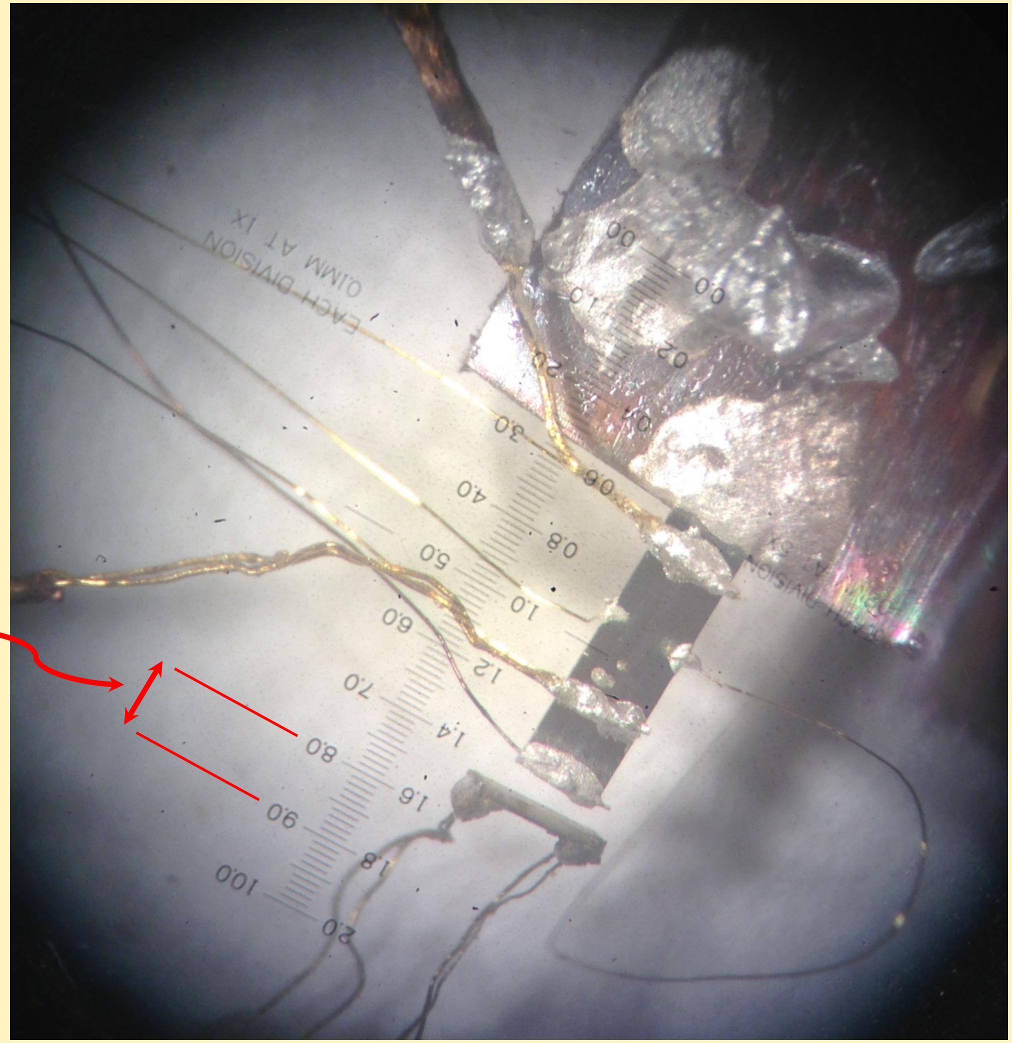




^{3}He "dipper" probe with 5-T magnet



Steady-state measurements, low-T

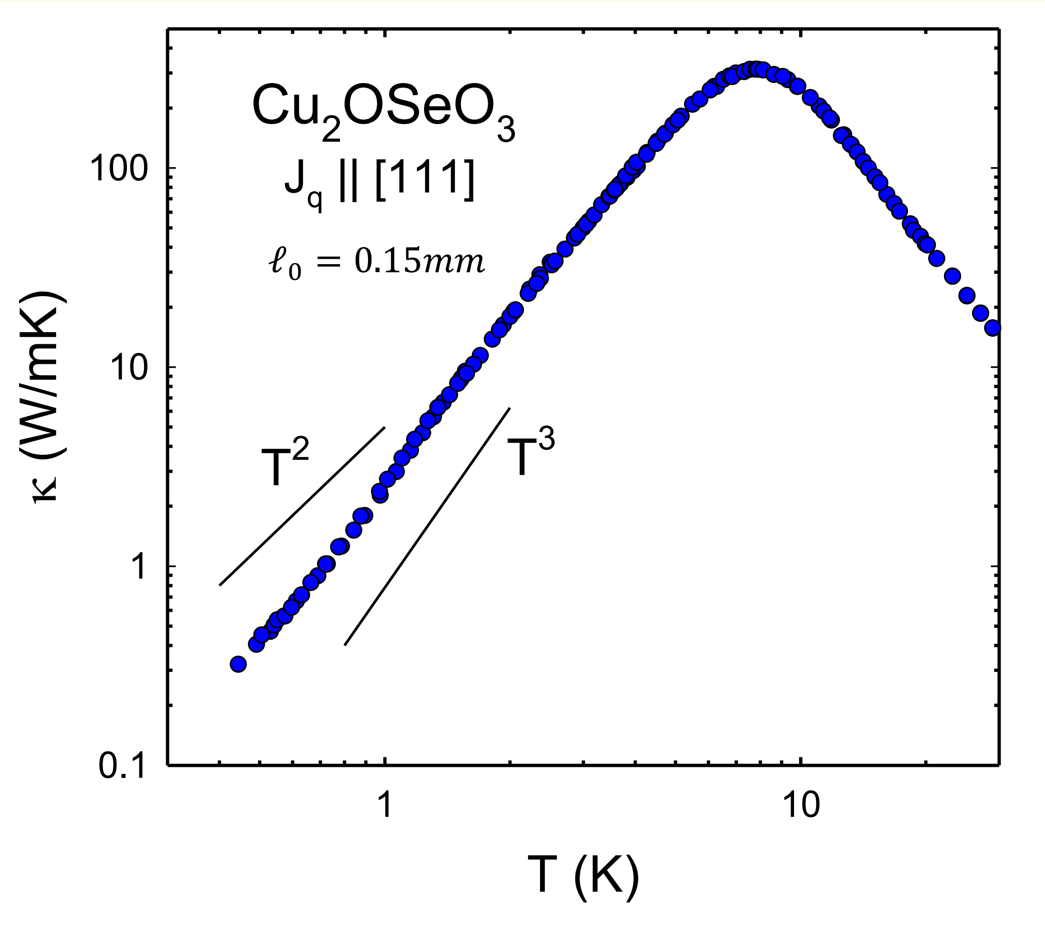


0.5 mm

Cu_2OSeO_3: κ(T) (zero applied field)

κ(8K) ≈ 300-350 W/mK

High quality of lattice



Prasai *et al.*, Phys. Rev. B **95**, 224407 (2017)

$$\kappa \cong \kappa_L + \kappa_m$$

magnon contribution

Sanders and D. Walton, Phys. Rev. B **15**, 1489 (1977)

Separating κ_m and κ_L

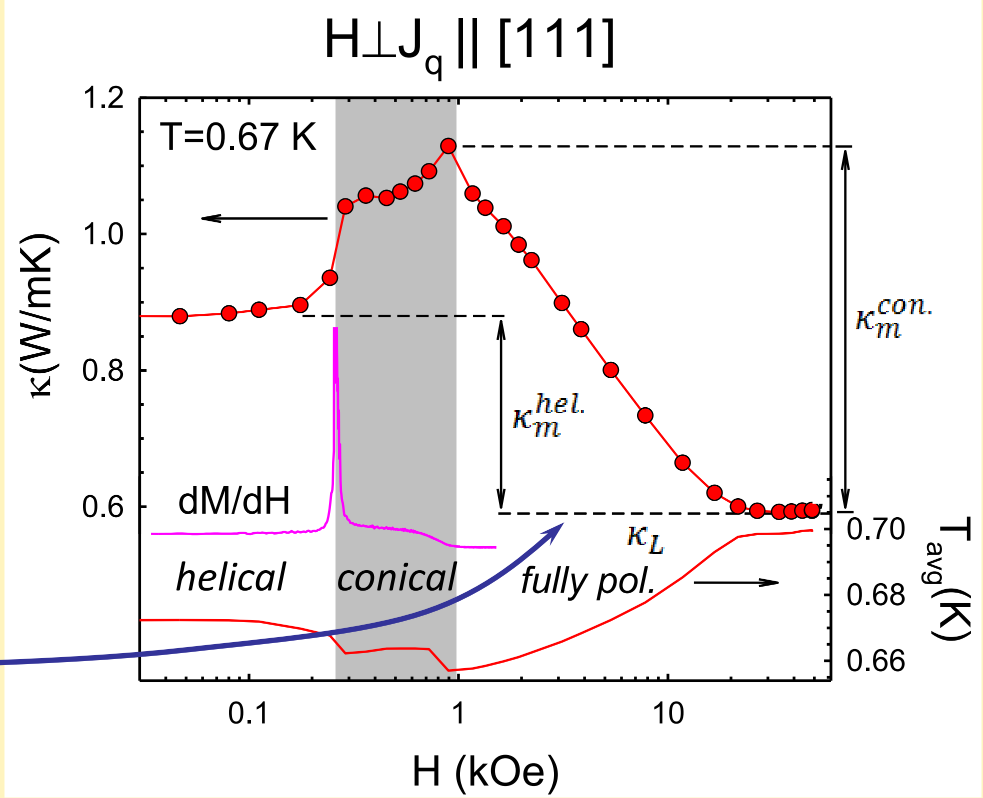
Spin wave energy

$$\hbar\omega = Dq^2 + \mu_B g H$$

Spin waves de-populated

magnon gap: $\mu_B g H \gg k_B T$

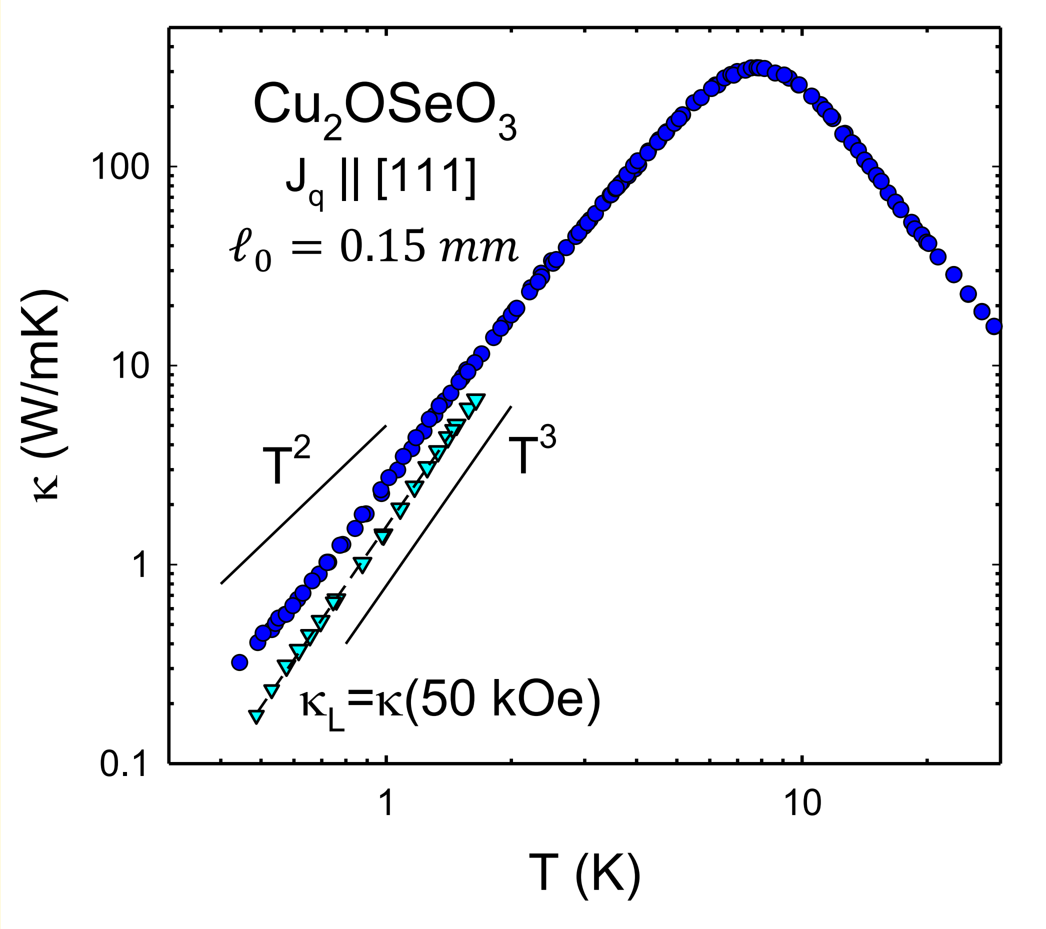
$$(\mu_B g / k_B \cong 1.4\ K/Tesla)$$



Prasai *et al.*, Phys. Rev. B **95**, 224407 (2017)

Separating κ_m and κ_L

Prasai *et al.*, Phys. Rev. B **95**, 224407 (2017)



At T<2K:

$$\kappa_L \propto T^3$$

➡ Boundary-limited phonon scattering at T<2K

$$\ell_{ph} \cong \frac{3\kappa_L}{C_L v_{ph}} = 0.16\,mm$$

At T<1K:

$$\kappa_m = \kappa(H) - \kappa_L \propto T^2$$

➡ Boundary-limited magnon scattering

$$\left\{ \text{For } \ell_m = const.,\ \kappa_m \propto T^2 \int_0^\infty \frac{x^3 e^x}{(e^x - 1)^2} dx \right\}$$

Separating κ_m and κ_L

Prasai *et al.*, Phys. Rev. B **95**, 224407 (2017)

At T<2K:

$$\kappa_L \propto T^3$$

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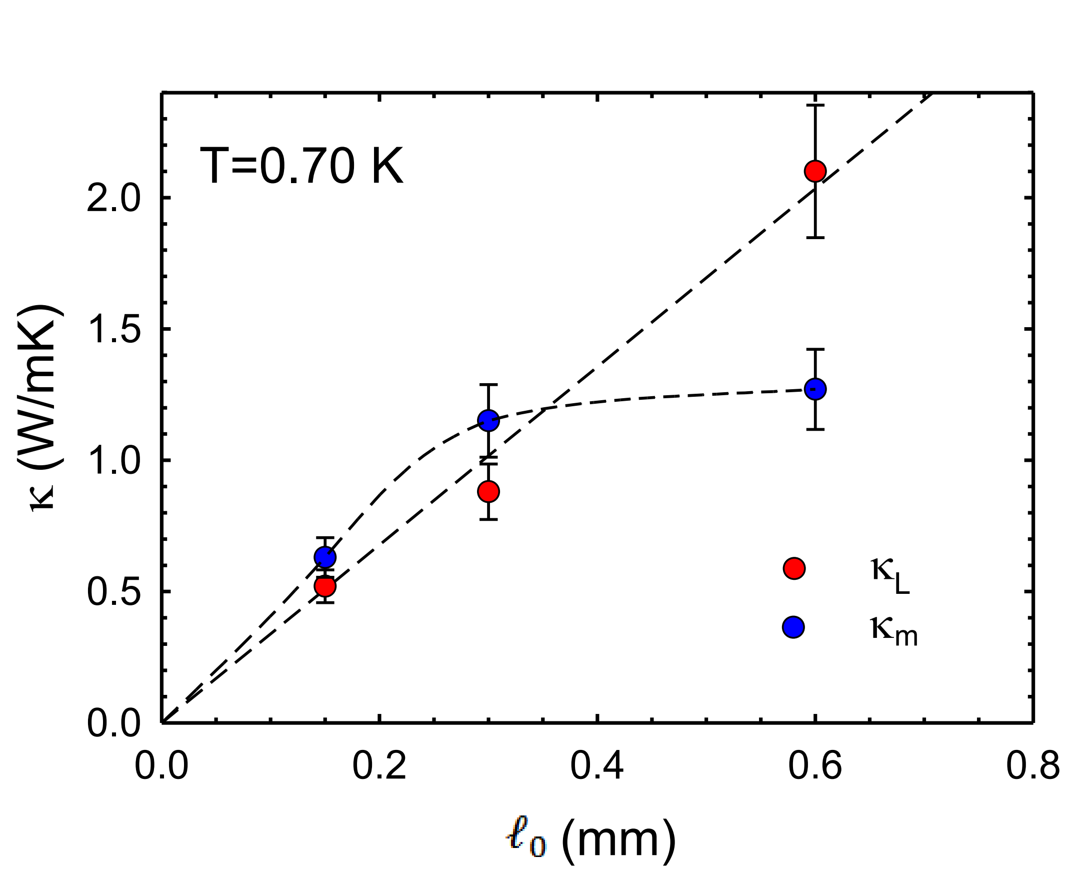
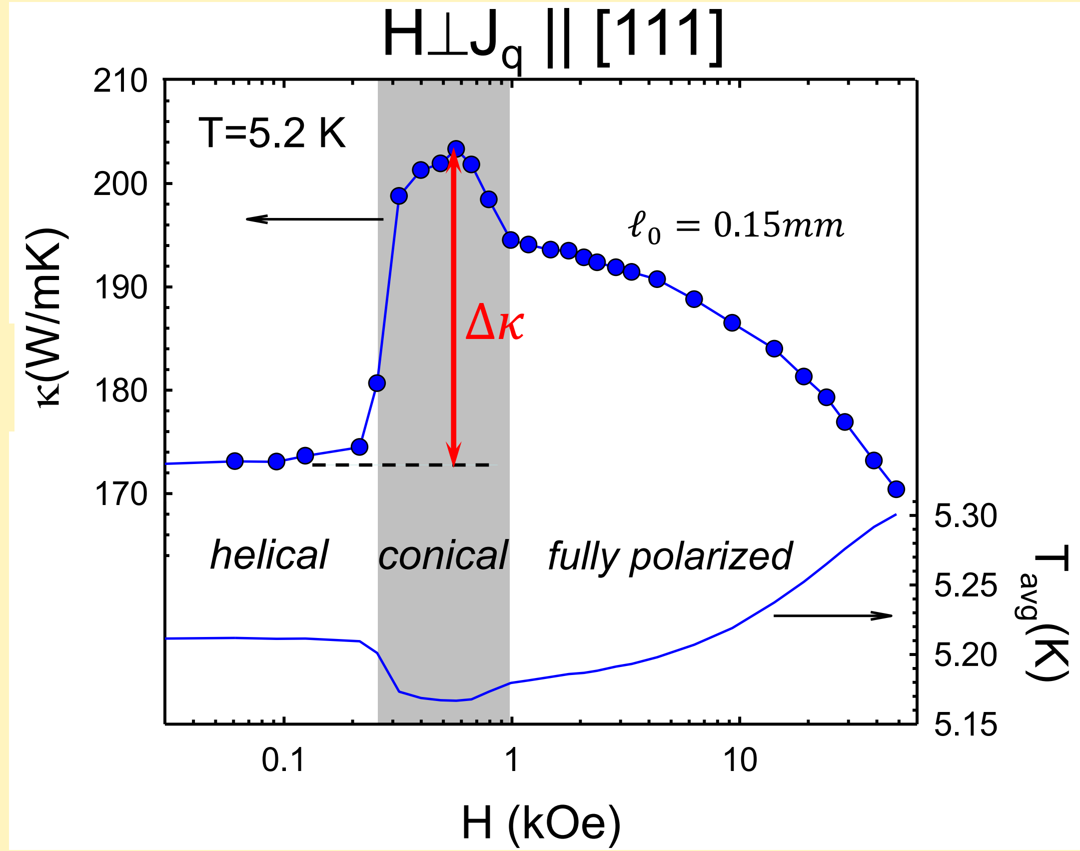
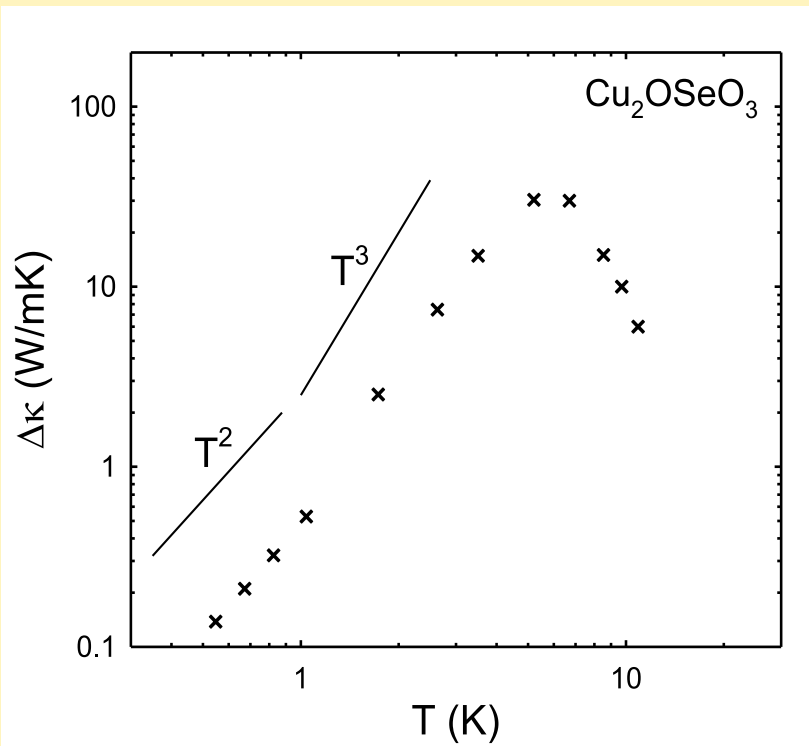


➡ Boundary-limited magnon scattering

$$\left\{ \text{For } \ell_m = const.,\ \kappa_m \propto T^2 \int_0^\infty \frac{x^3 e^x}{(e^x - 1)^2} dx \right\}$$

Estimating κ_m, T>2K





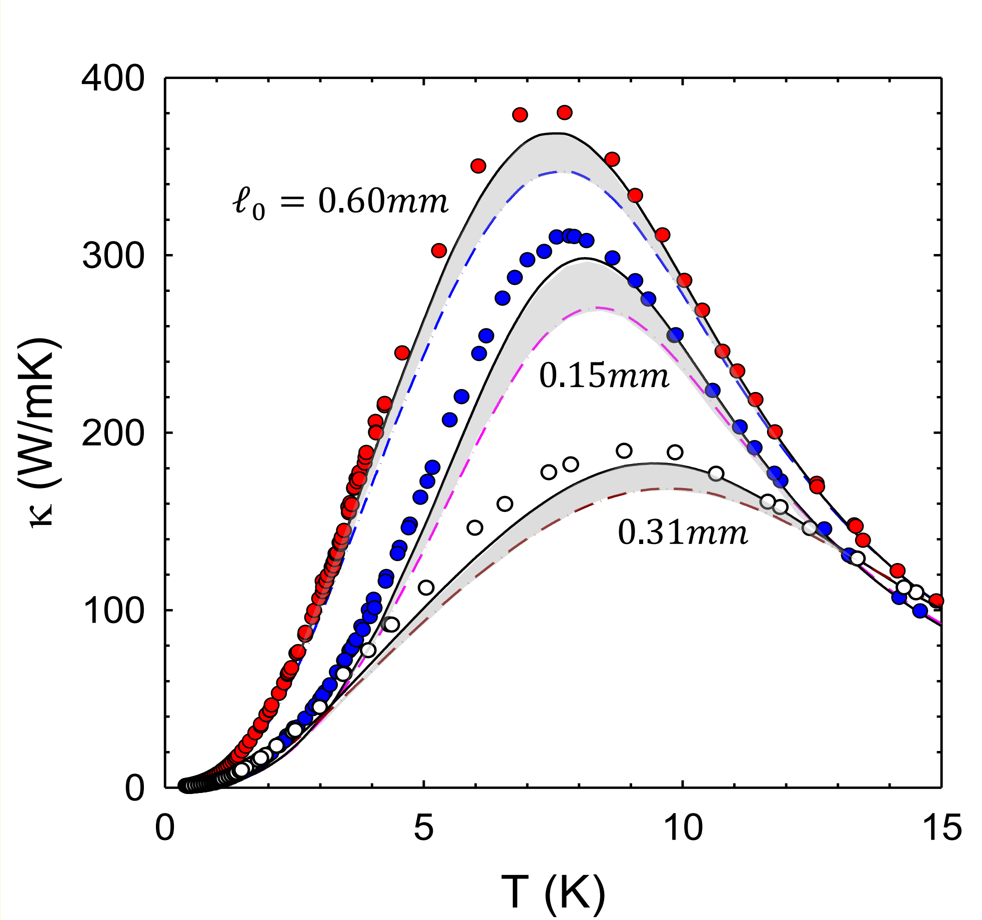
Lower bound on $\kappa_m^{con.}$

$\kappa \approx \kappa_L$ at T>12 K

Prasai *et al.*, Phys. Rev. B **95**, 224407 (2017)

Estimating κ_m, T>2K

Callaway model fitting,
constrained by low-T,
hi-T data, max. in κ_m at T=5-6 K.

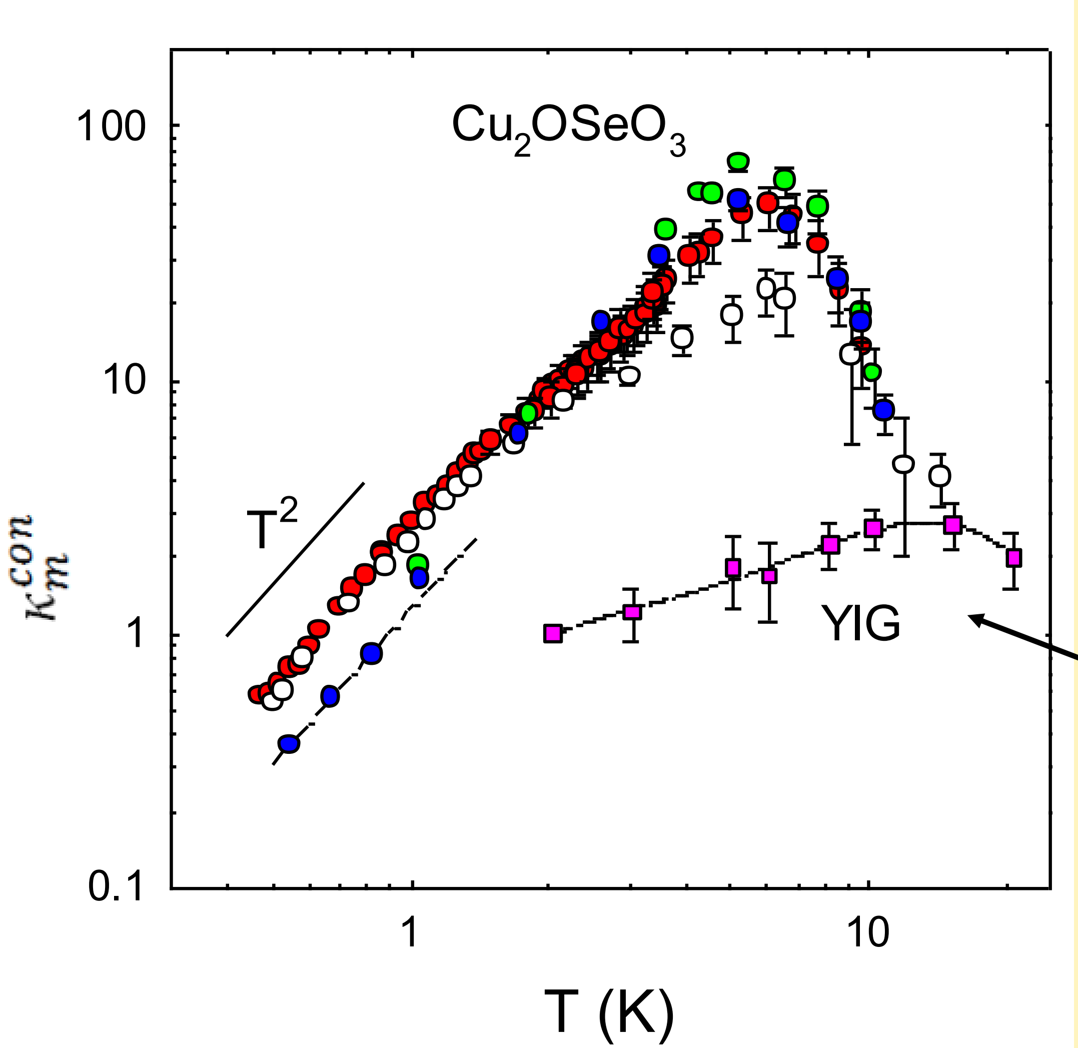


$$\kappa_L = \frac{k_B}{2\pi^2 v}\left(\frac{k_B}{\hbar}\right)^3 T^3 \int_0^{\Theta_D/T} \frac{x^4 e^x}{(e^x - 1)^2}\tau(x, T)dx,$$

Prasai *et al.,* Phys. Rev. B **95**, 224407 (2017)

Magnon thermal conductivity

the record for a ferro- or ferrimagnet…



Boona and Heremans, PRB **90**, 064421 (2014)

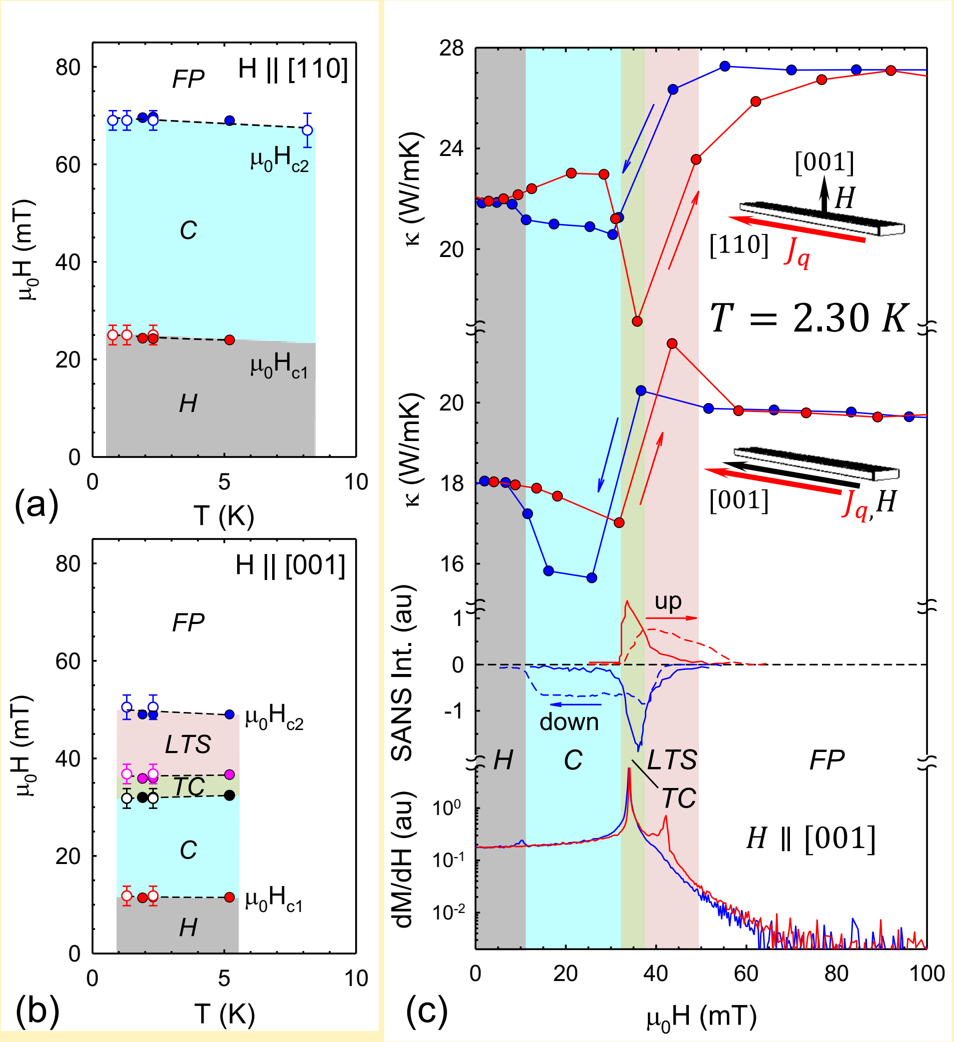
Prasai *et al.,* Phys. Rev. B **95**, 224407 (2017)

Novel spin phases, *H* ∥ [100]

- Tilted conical (TC)
- Low-T skyrmion (LTS)

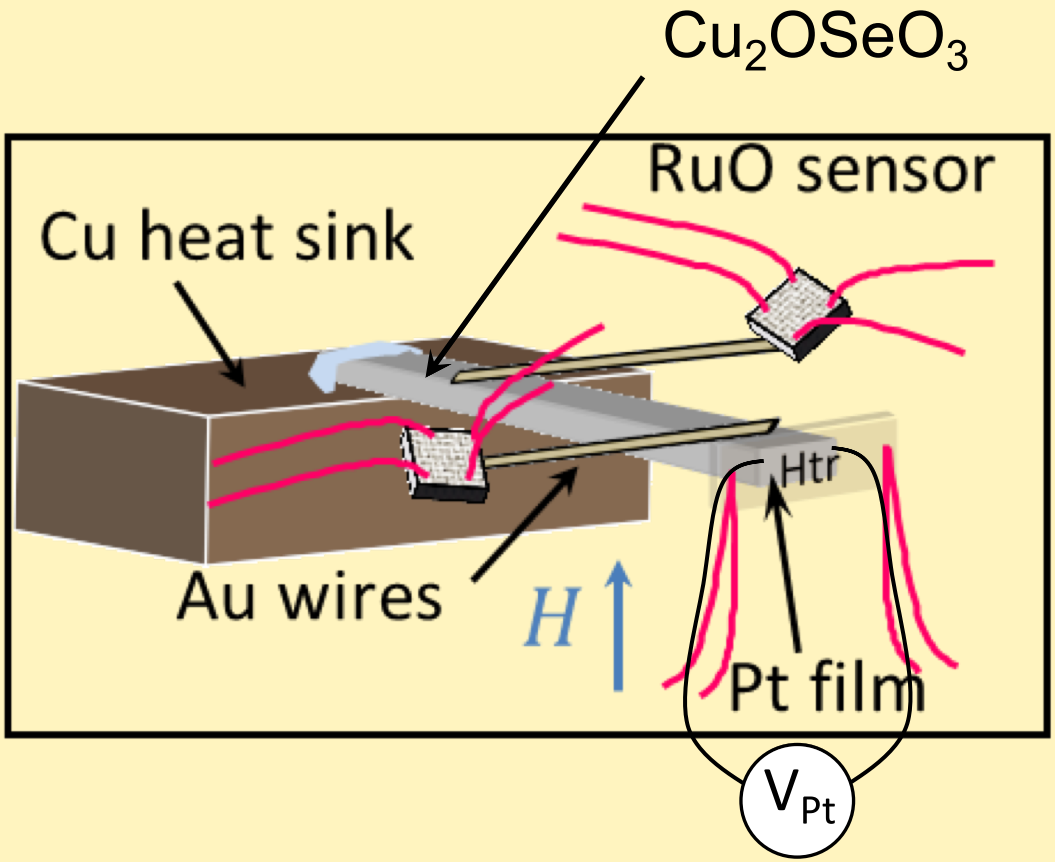
small-angle neutron scattering

A. Chacon *et al*., Nat. Phys.**14**, 936 (2018)
F. Qian *et al*., Sci. Adv. **4**, 7323 (2018)



Prasai *et al.*, Phys. Rev. B **99**, 020403 (R) (2019)

Spin Seebeck Effect at T< 20 K

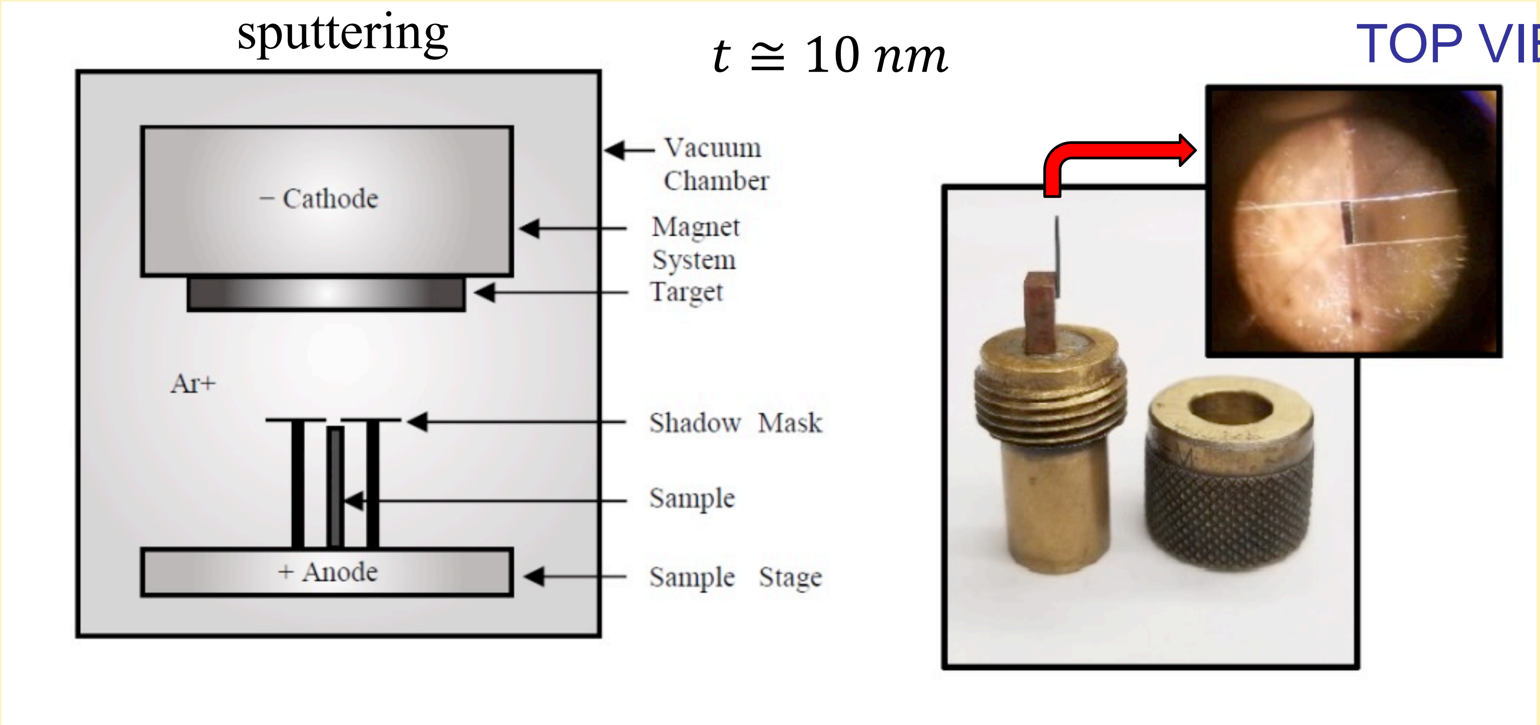


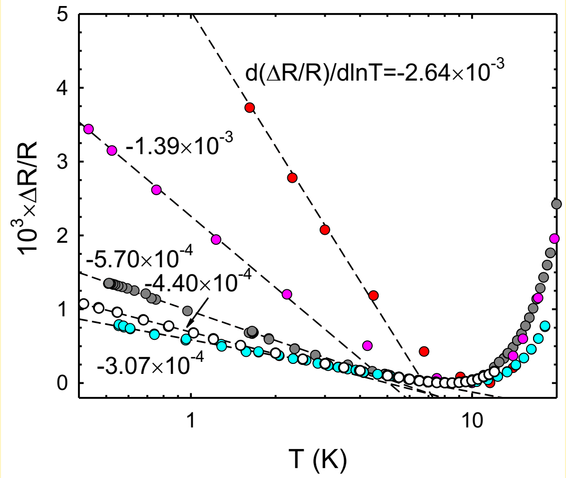
Three specimens: crystal 1 $\left\{ \begin{array}{l} \ell_0 = 0.60mm \\ \ell_0 = 0.47mm \end{array} \right.$ ⟸ best signal ($g_{eff}^{\uparrow\downarrow}$)

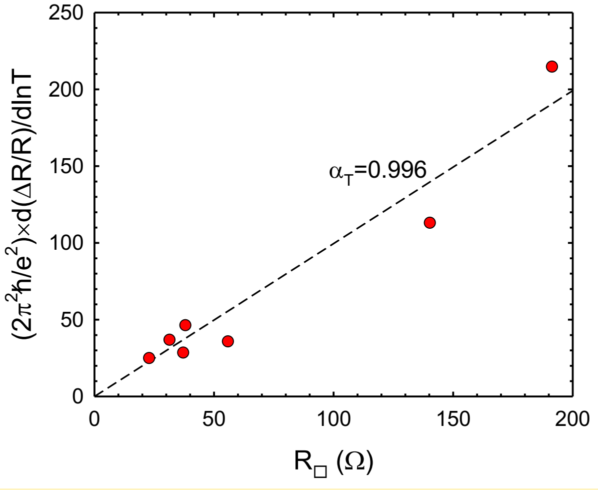
crystal 2 $\ell_0 = 0.31mm$

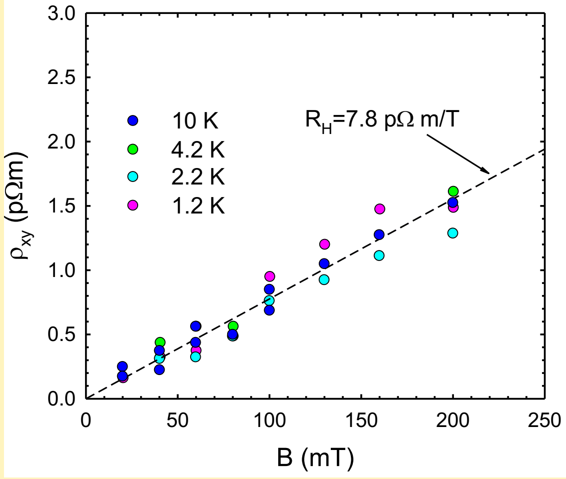
Spin-mixing conductance varies by $> 10\times$

Pt film deposition and properties





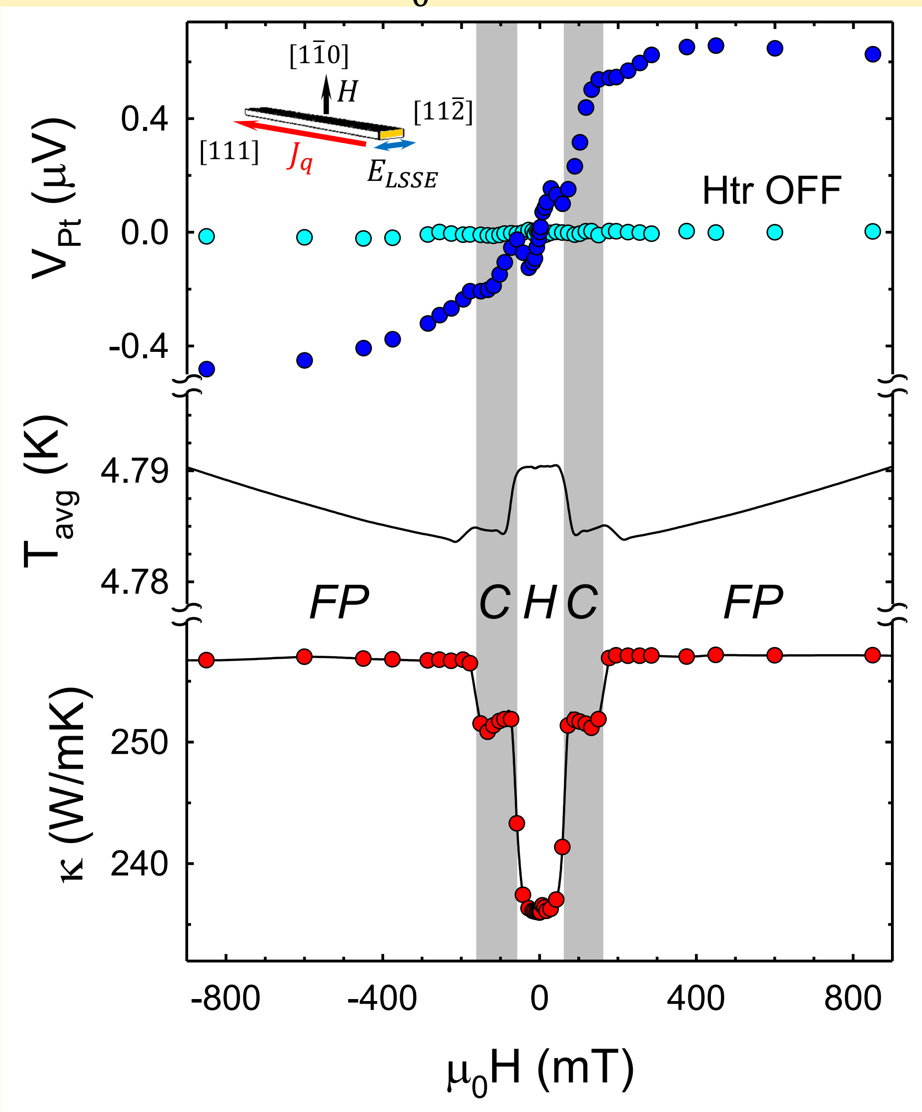


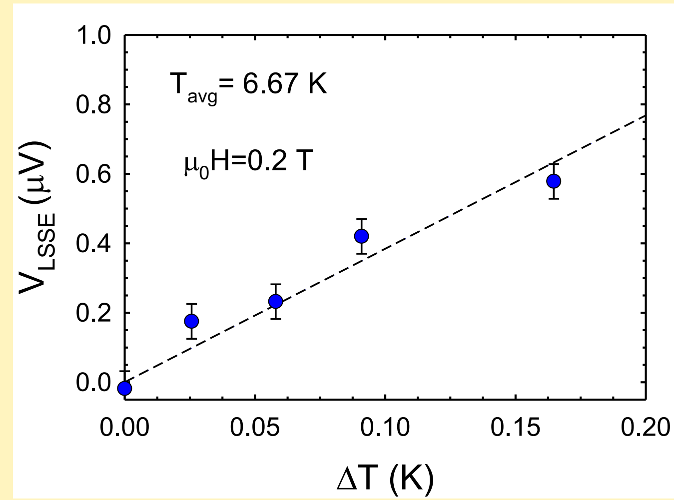


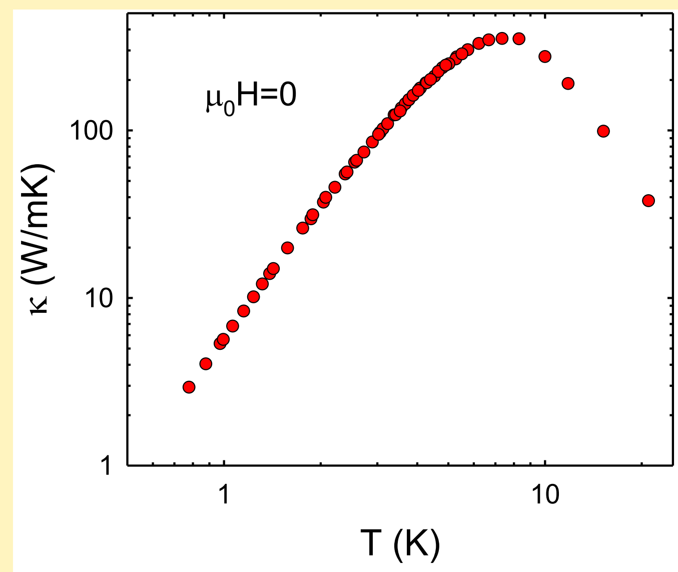
Spin Seebeck Effect at T< 20 K

$$V_{LSSE} = \frac{V_{Pt}(H) - V_{Pt}(-H)}{2}$$

$\ell_0 = 0.47mm$







S_{LSSE}, κ_m Field dependence

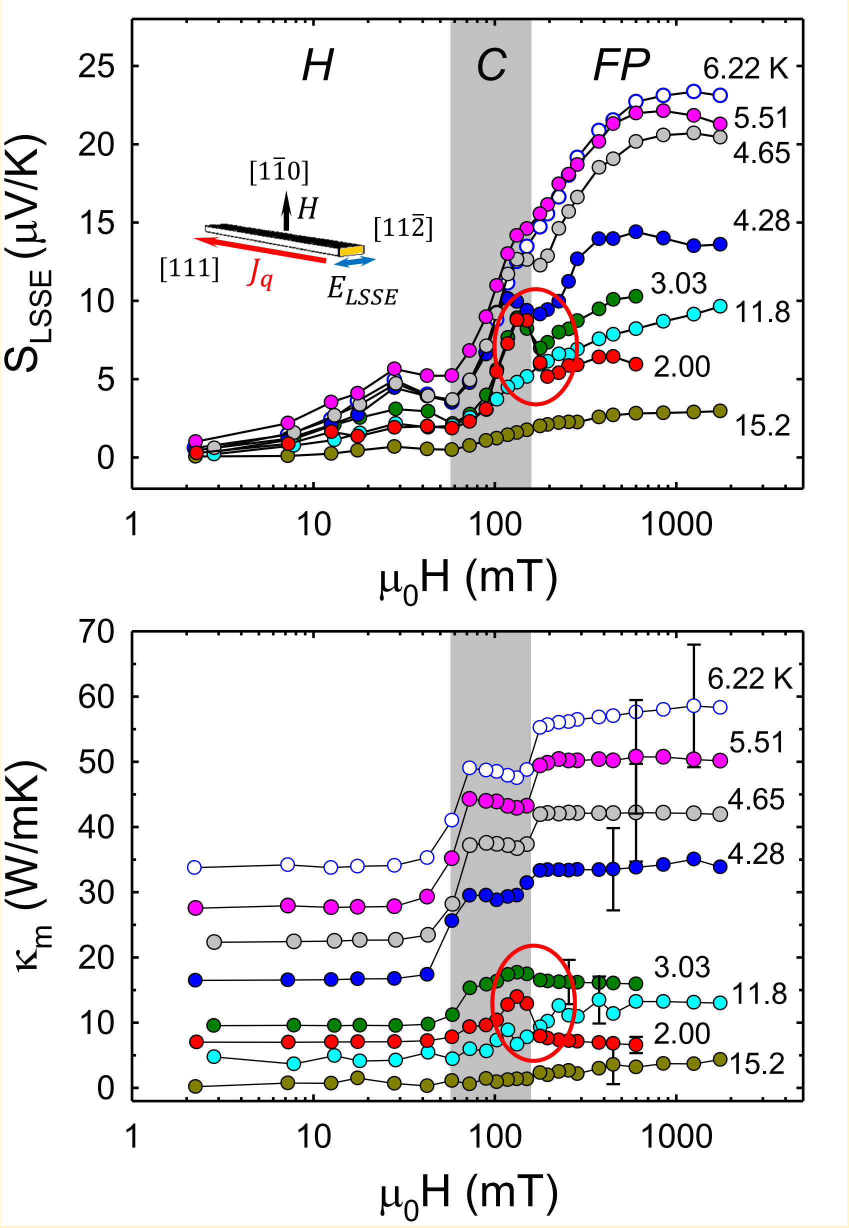
$$S_{LSSE} = \frac{E_{ISHE}}{\nabla T}$$

$\ell_0 = 0.47mm$

κ_m, S_{LSSE}: close correspondence

C-FP transition:

- Sharp decrease in magnitude T=2.00, 3.03 K (larger spin gap in FP phase, $\Delta \approx 0.2\ meV$)



S_{LSSE}, κ_m Field dependence

$$S_{LSSE} = \frac{E_{ISHE}}{\nabla T}$$

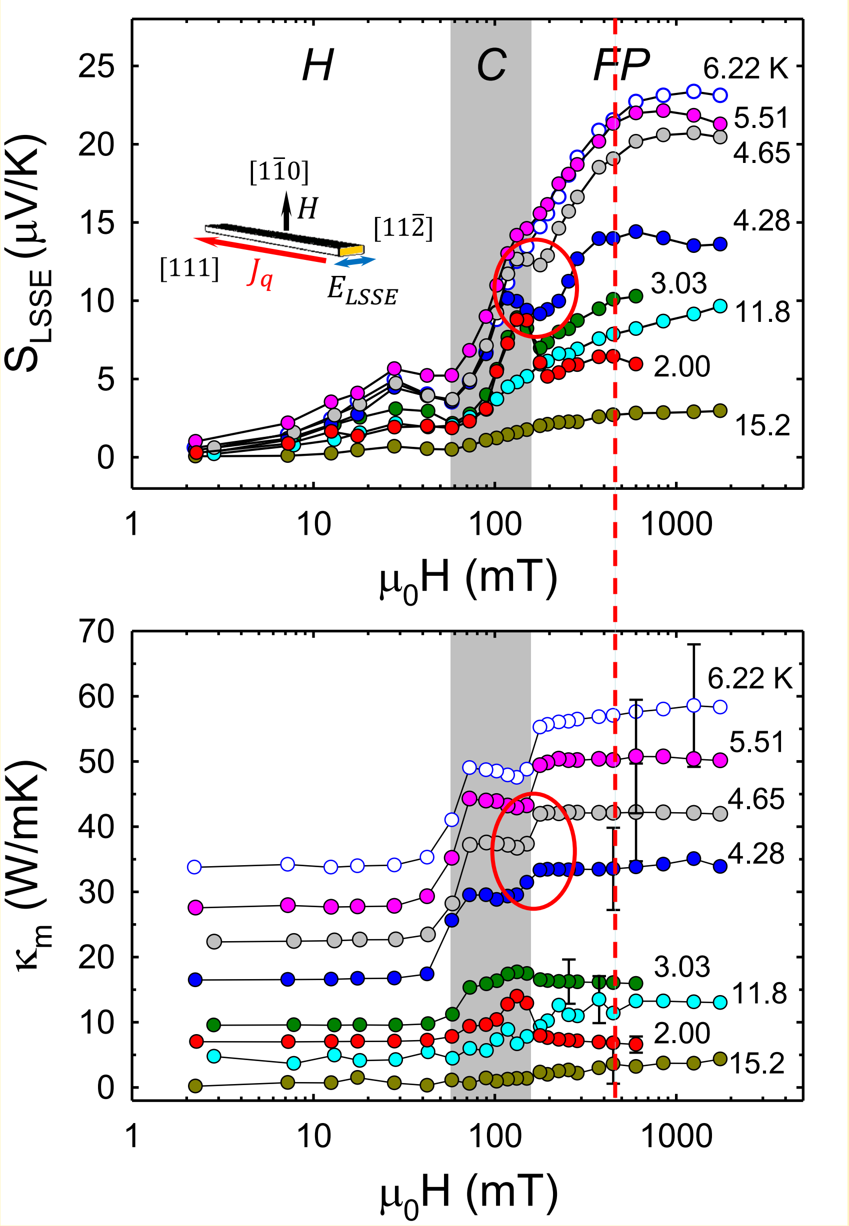
$\ell_0 = 0.47mm$

κ_m, S_{LSSE}: close correspondence

C-FP transition:

- Sharp decrease in magnitude T=2.00, 3.03 K (larger spin gap in FP phase, $\Delta \approx 0.2\ meV$)
- Decrease appears at higher T for S_{LSSE}

➡ *Subthermal* magnon role in spin-Seebeck effect



S_{LSSE}, κ_m T dependence

Zhang & Zhang, PRL **109**, 096603 (2012)
Rezende *et al.*, JMMM **400**, 171 (2016)

$$x = \frac{\hbar\omega}{k_B T} \qquad \ell_0 = 0.47mm$$

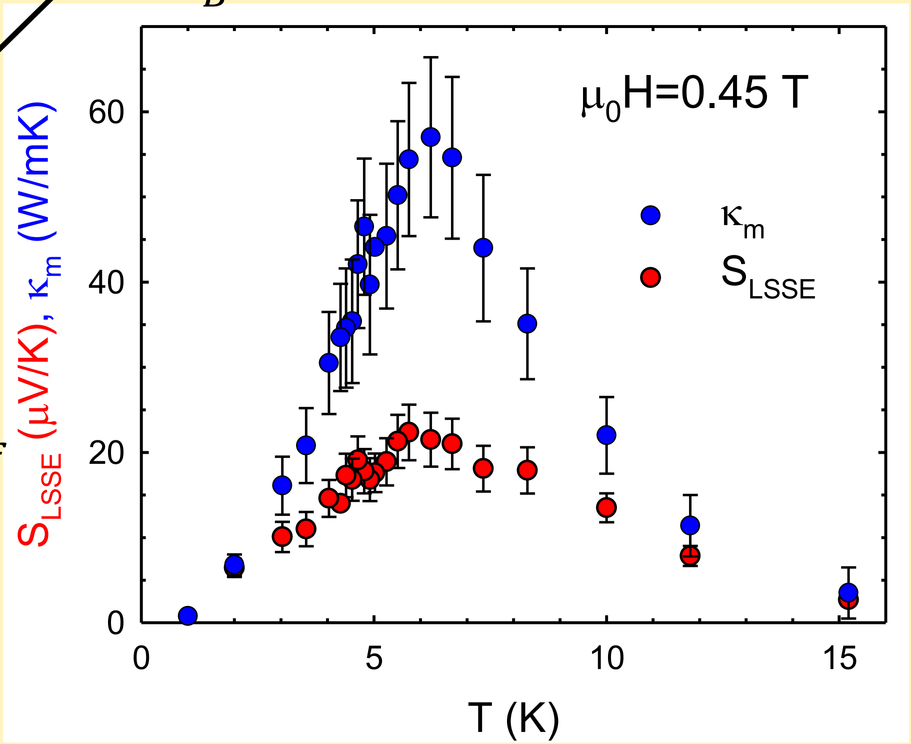
$$\kappa_m = \frac{k_B}{6\pi^2}\int_0^{q_m} dq\, q^2 v_m^2 \tau_R \frac{x^2 e^x}{(e^x - 1)^2}$$

$$S_{LSSE} = R_N \lambda_N \frac{2e}{\hbar}\theta_H \frac{B_{11}C_2}{(B_{10}C_1)^{1/2}} F g_{eff}^{\uparrow\downarrow}$$

$$F \propto (\tau_m \tau_{th})^{1/2}$$

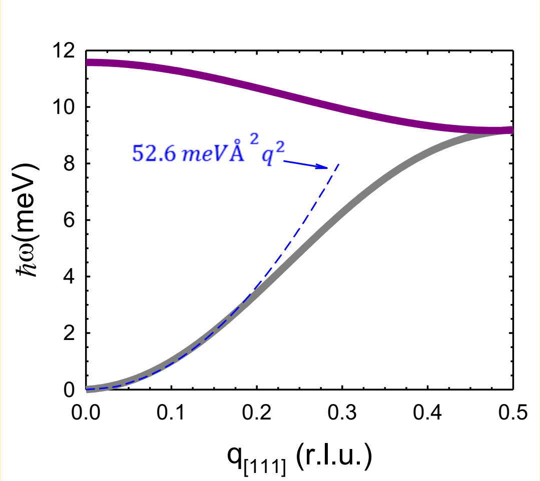
$(\tau_{th} \gg \tau_m)$

T dependent



magnon dispersion

$$\hbar\omega = \Delta + g\mu_B H + 4.55\, meV\left[1 - \cos\left(\frac{\pi q}{q_m}\right)\right]$$



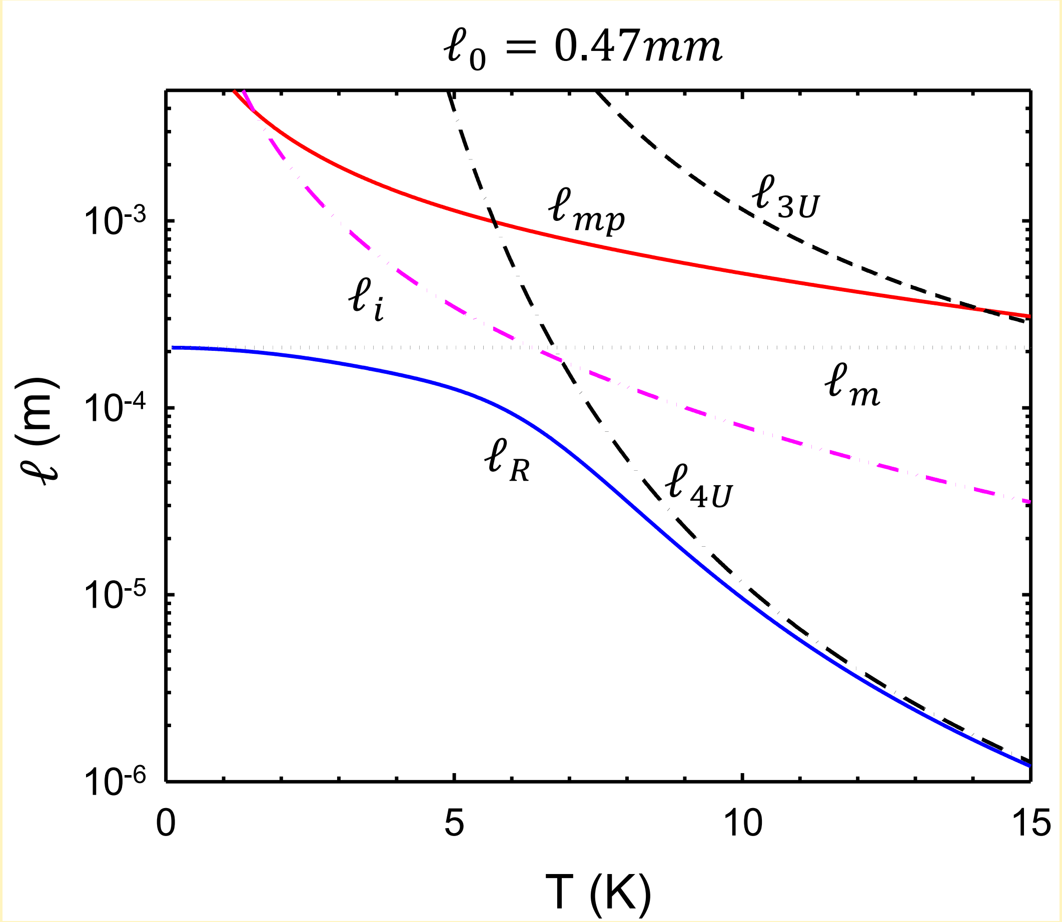
Portnichenko *et al.*, Nature Commun. **10**, 10725 (2016)

S_{LSSE}, κ_m T dependence

κ_m -- scattering rate (τ_R^{-1})

Forney and Jäckle, Phys. kondens. Materie **16**, 147 (1973)

(EuS, T_C=16.5 K)



magnon-magnon Umklapp

$\tau_{3U}^{-1}, \tau_{4U}^{-1}$

magnon-impurity (non-mag.)

τ_i^{-1}

magnon-boundary

$\tau_b^{-1} = \langle v_m \rangle / \ell_m \quad (\ell_m \leq \ell_0)$

$$\tau_R^{-1} = \tau_{4U}^{-1} + \tau_i^{-1} + \tau_b^{-1}$$

$\tau_{mp}^{-1} \simeq 2 \times 10^5 T^{3/2}$ [estimated from FMR linewidth, PRB **93**, 235131 (2016)]

A. I. Akhiezer, V. G. Bar'yakhtar, M. I. Kaganov, Soviet Phys. Uspekhi **3**, 661 (1961)

F. Schwabl and K. H. Michel, PRB **2**, 189 (1970)

S_{LSSE}, κ_m T dependence

$$S_{LSSE} \propto (\tau_m \tau_{th})^{1/2} \dots$$

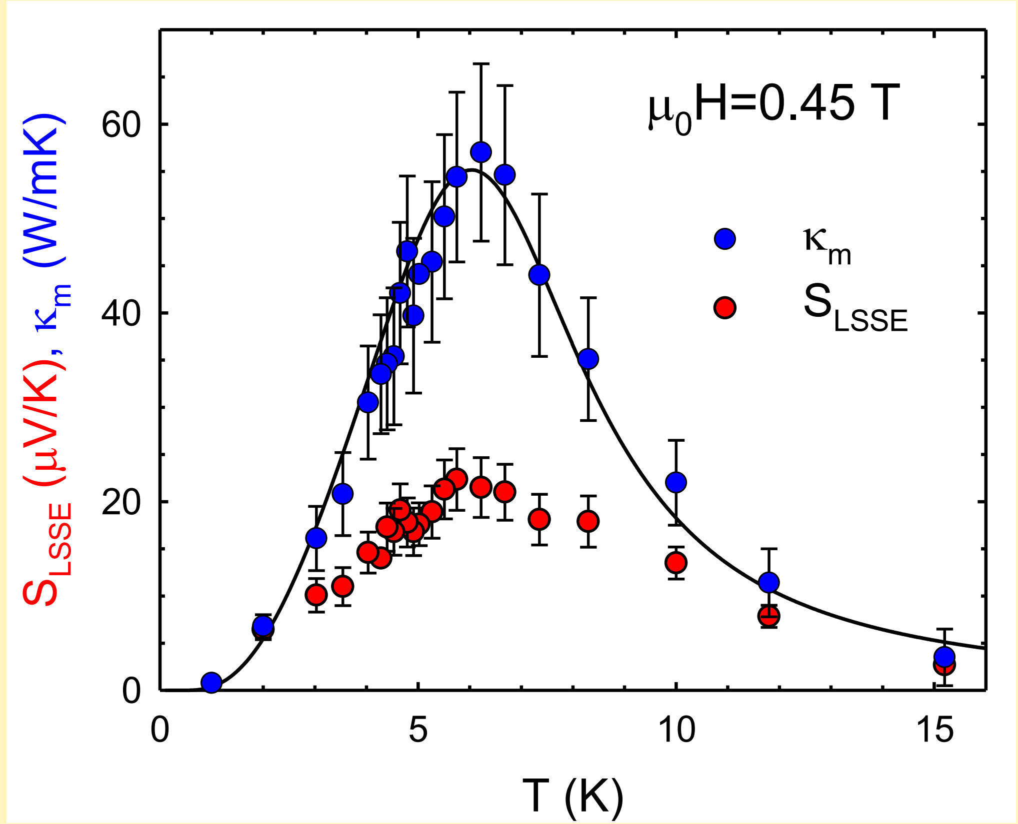
magnon number conserving

magnon number non-conserving

$$\tau_m = \tau_R$$

$$(\tau_R^{-1} = \tau_{4U}^{-1} + \tau_i^{-1} + \tau_b^{-1})$$

$$\ell_0 = 0.47mm$$



S_{LSSE}, κ_m T dependence

$$S_{LSSE} \propto (\tau_m \tau_{th})^{1/2} \ldots$$

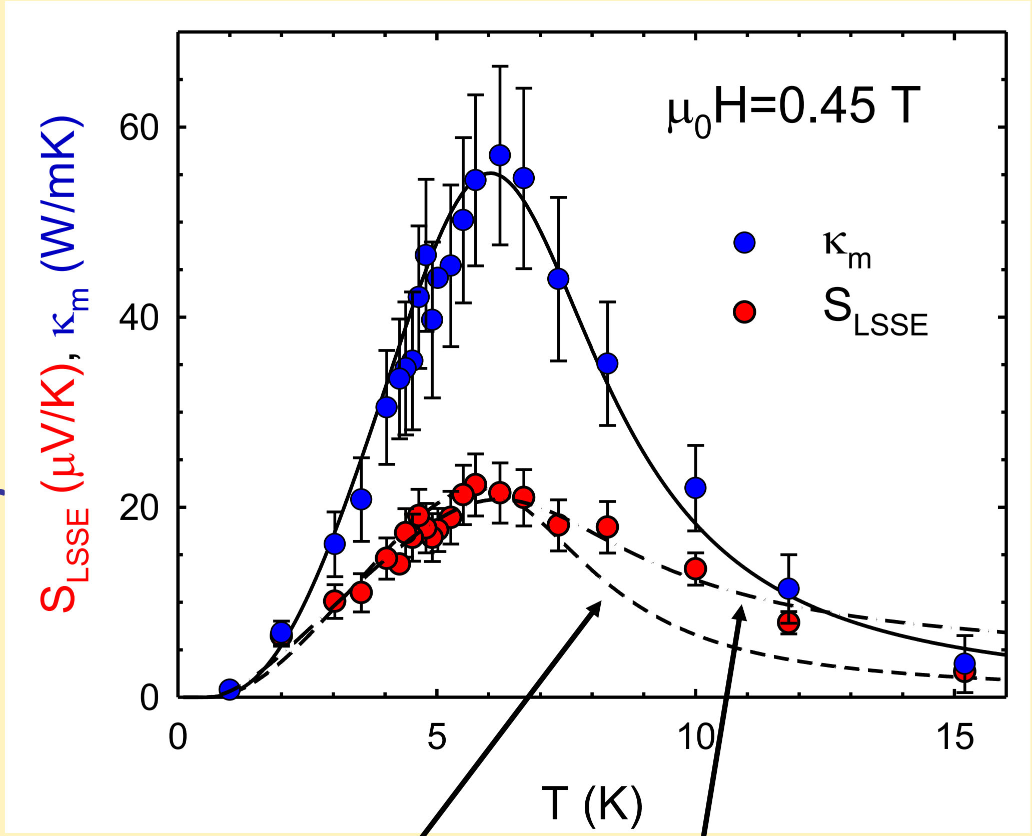
magnon number conserving

magnon number non-conserving

$$\tau_m = \tau_R$$

$$(\tau_R^{-1} = \tau_{4U}^{-1} + \tau_i^{-1} + \tau_b^{-1})$$

$\ell_0 = 0.47mm$

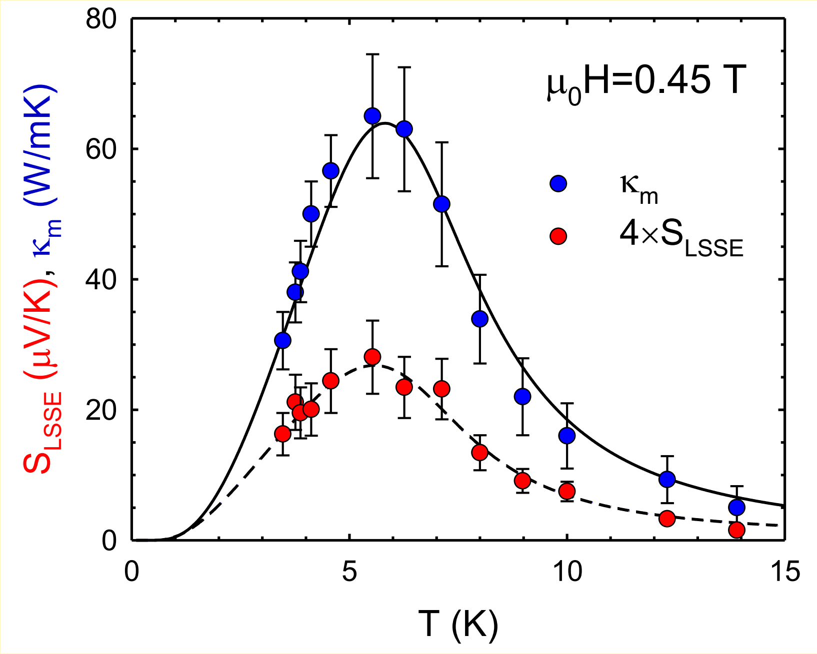


$$\tau_{th} \propto \tau_R$$

$$\tau_{th}^{-1} = \tau_{mp}^{-1} + \tau_{3N}^{-1} + \tau_{3U}^{-1}$$

S_{LSSE}, κ_m T dependence

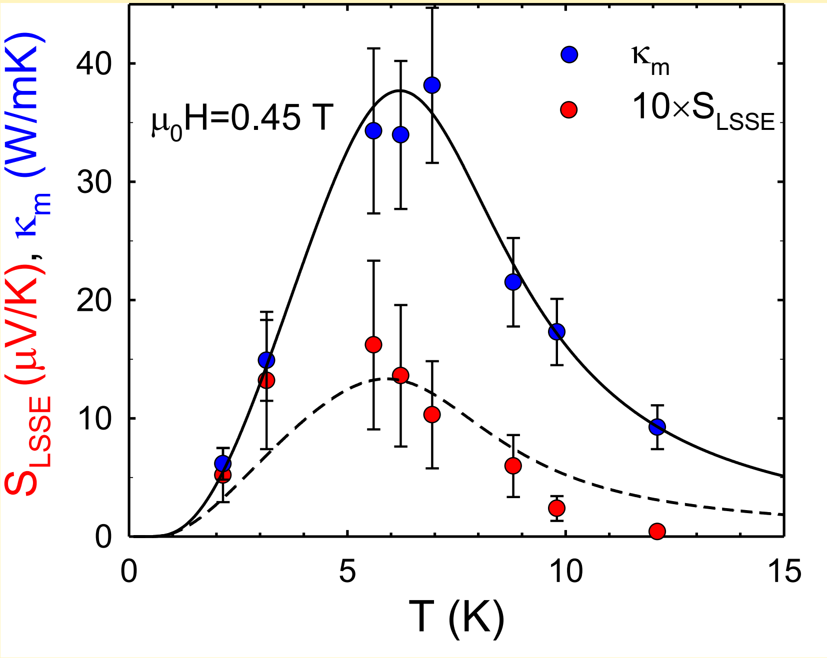
$\ell_0 = 0.60\ mm$



Better fits with

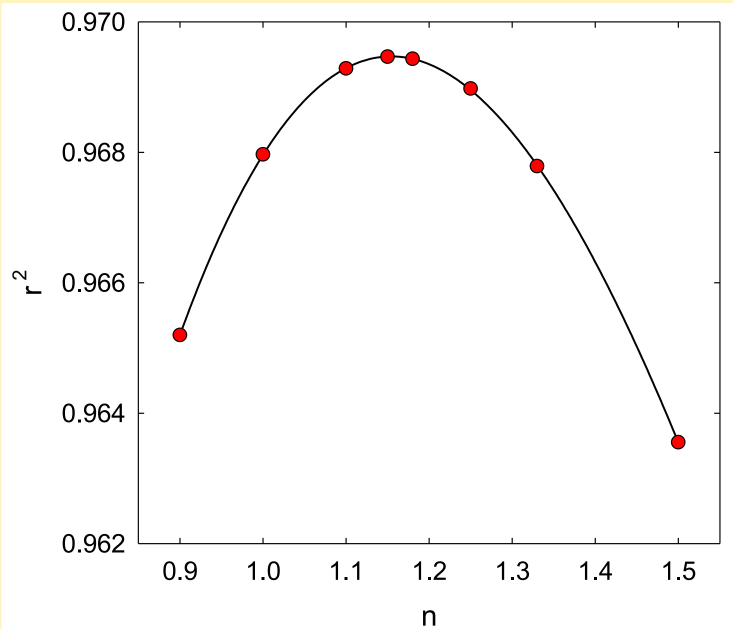
$\tau_{th} \propto \tau_R$

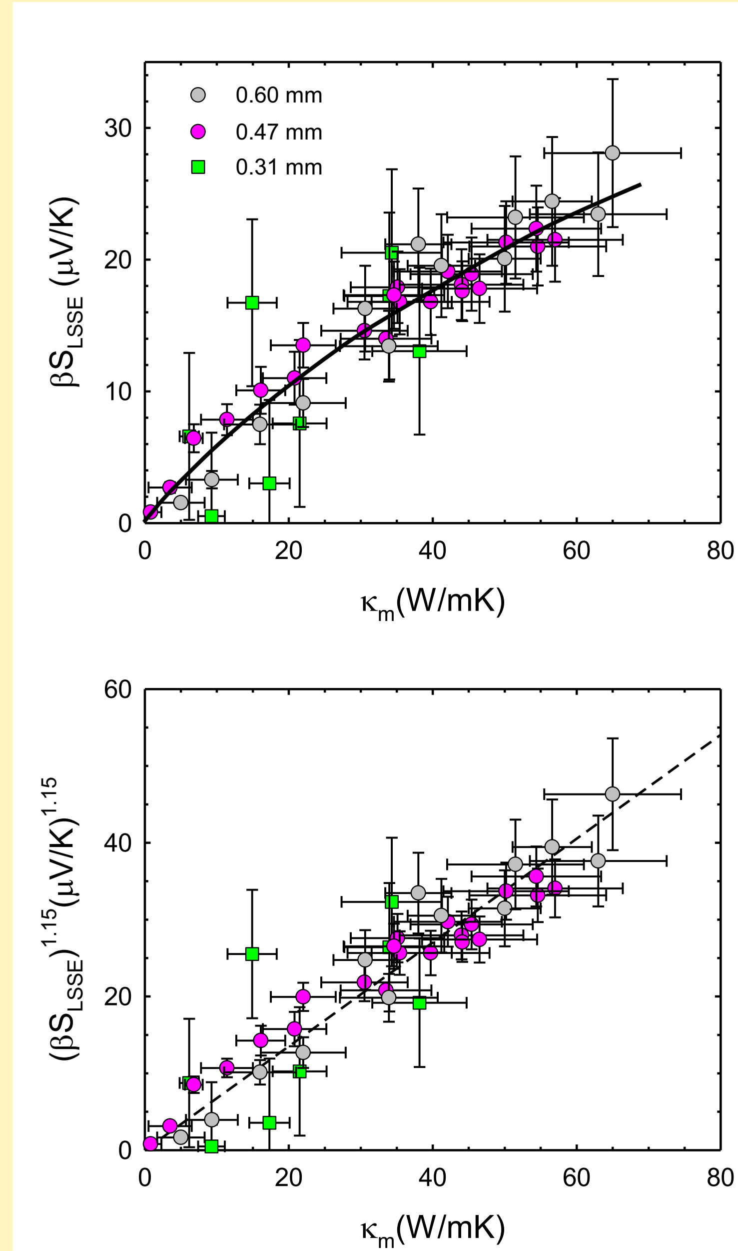
$\ell_0 = 0.31\ mm$



S_{LSSE}, κ_m integrals

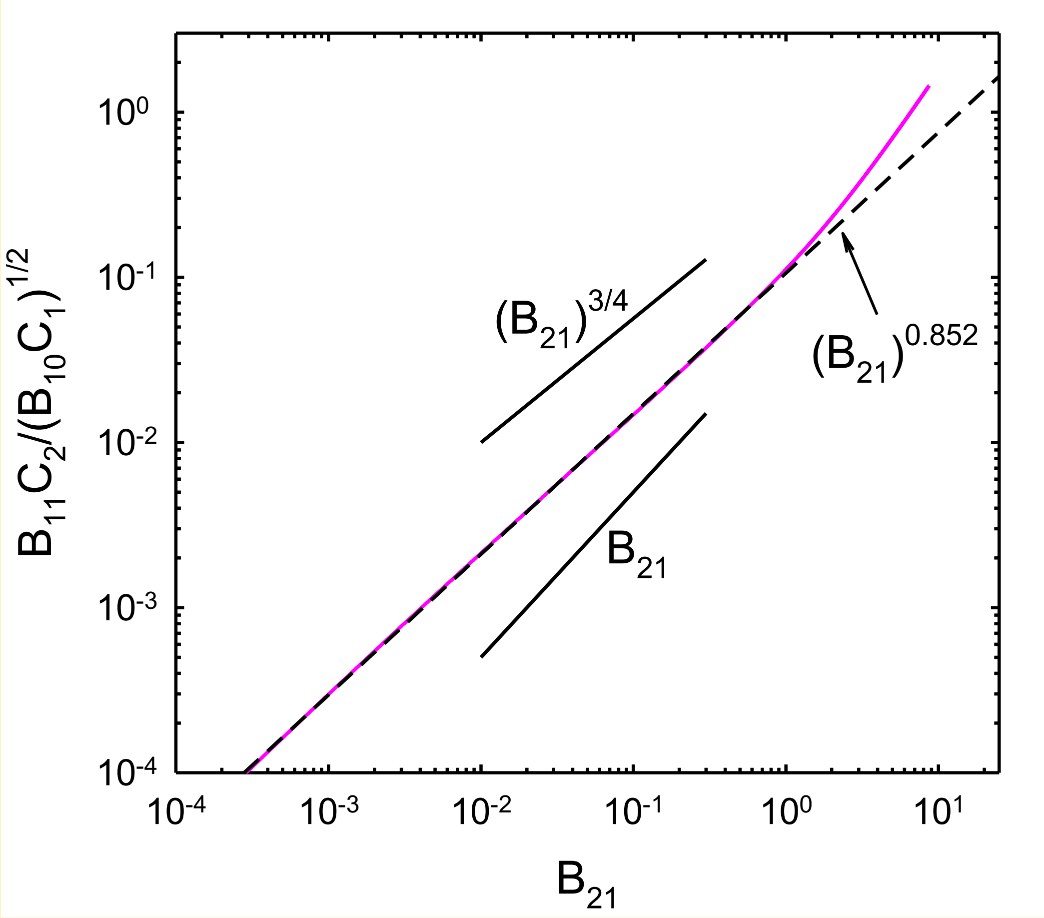
Re-scaled S_{LSSE}





Specimen	ℓ_0 (mm)	c(ppm)	ℓ_m (mm)	R_N (Ω)	$g_{eff}^{\uparrow\downarrow}$($10^{15}$m^{-2})
crystal 1	0.60	22	0.30	467	0.41
"	0.47	22	0.21	120	6.50
crystal 2	0.31	44	0.19	293	0.21

S_{LSSE}, κ_m integrals



If $\tau_{th} \propto \tau_R$,

$$S_{LSSE} \propto \kappa_m^{1.17}$$

$$B_{ij} = \int_0^1 dq q^2 v_m^2 \frac{x^i (e^x)^j}{(e^x - 1)^i}$$

$$\kappa_m \propto B_{21}$$

$$C_k = \int_0^1 dq q^2 \frac{x^k}{e^x - 1}$$

$$S_{LSSE} \propto \frac{B_{11} C_2}{(B_{10} C_1)^{1/2}}$$

Summary

- Cu_2OSeO_3: record magnon thermal conductivity
  (for ferro- ferri-magnets)
- Ballistic phonon and magnon transport at $T<2K$
- Large spin-Seebeck effect – tests of bulk theory