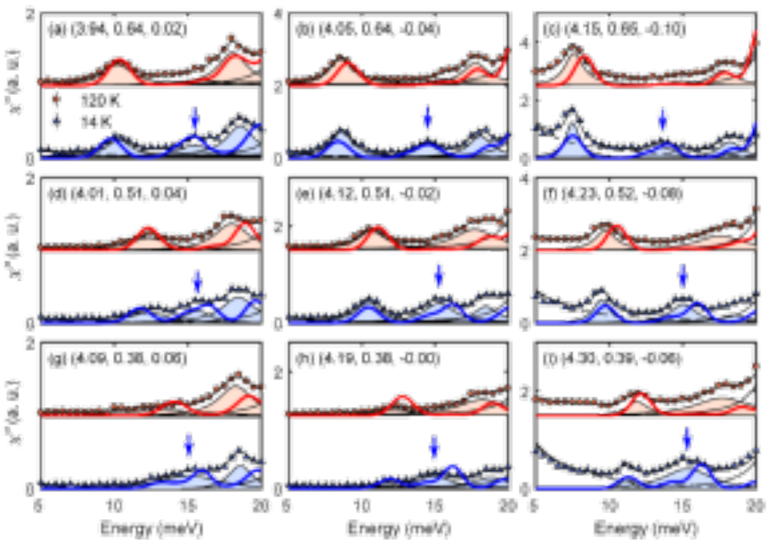
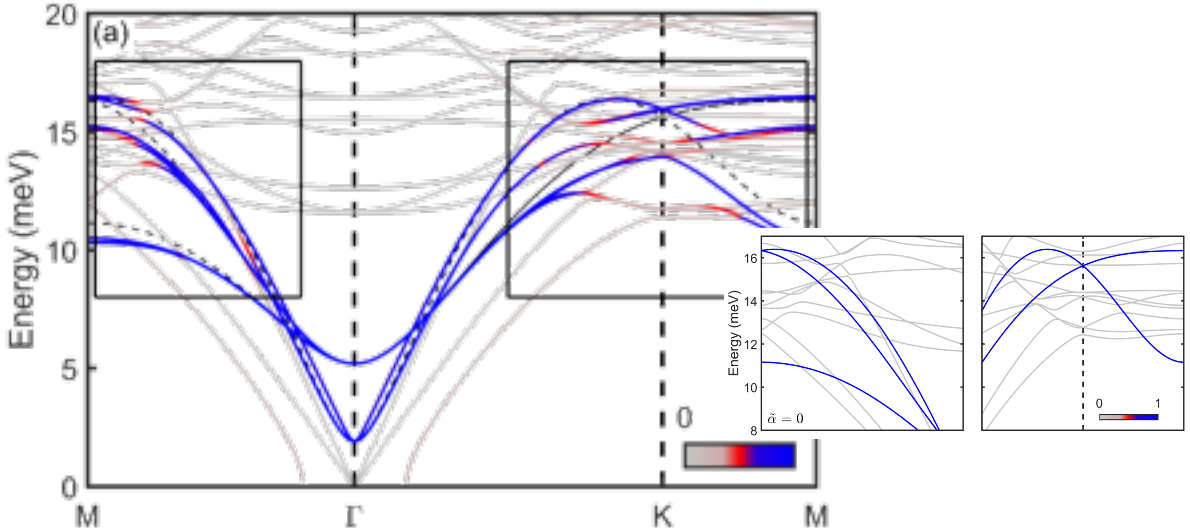
Magnon-magnon/phonon coupling in two-dimensional triangular lattice antiferromagnets





Je-Geun Park

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Dept. Physics & Astronomy

Seoul National University

Outline

- Why magnon-magnon/phonon coupling in 2D TAF?

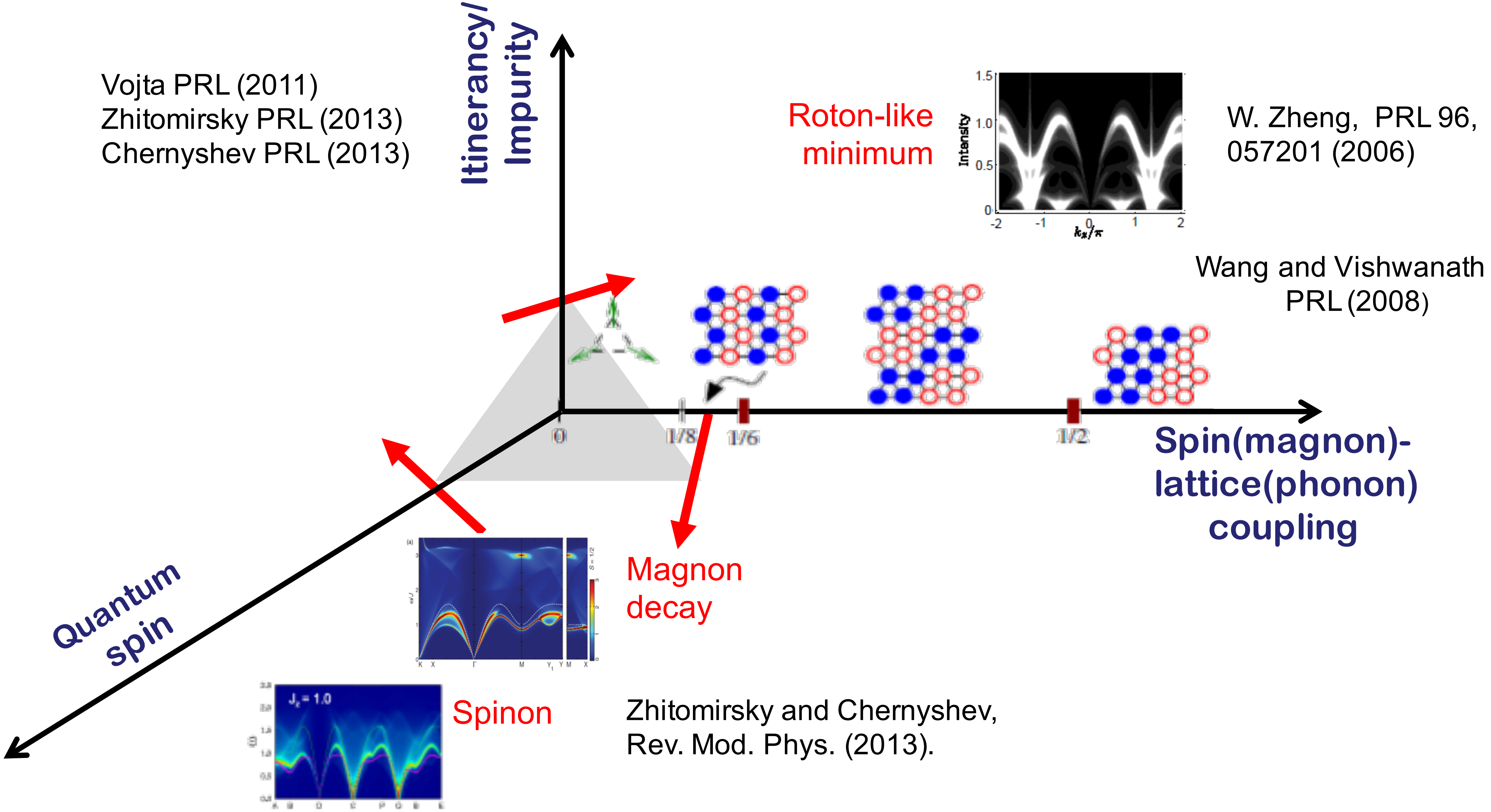
- A Tale of Two Cities: magnon-magnon/phonon couplings in $YMnO_3$
  - Magnons measured by inelastic neutron scattering
  - Phonons measured by inelastic X-ray scattering

- Outlook

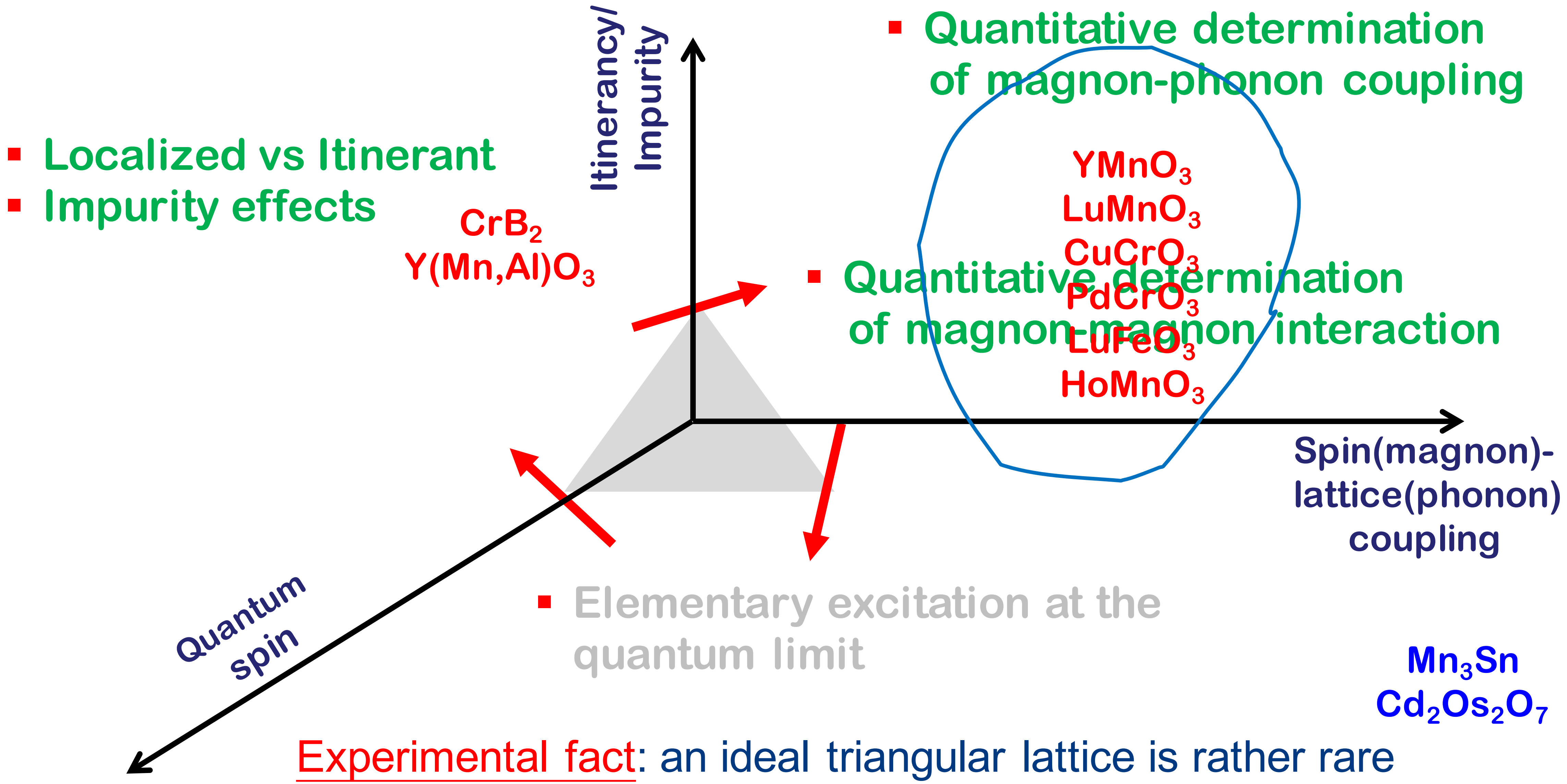

Posters

- Spin texture and its dynamics of Al-doped triangular lattice antiferromagnet h-$YMnO_3$, Kisoo Park
- Magnetic excitations in non-collinear metallic antiferromagnet CrB_2, Pyeongjae Park

Triangular Antiferromagnets



Triangular Antiferromagnets at J-G Park's Group



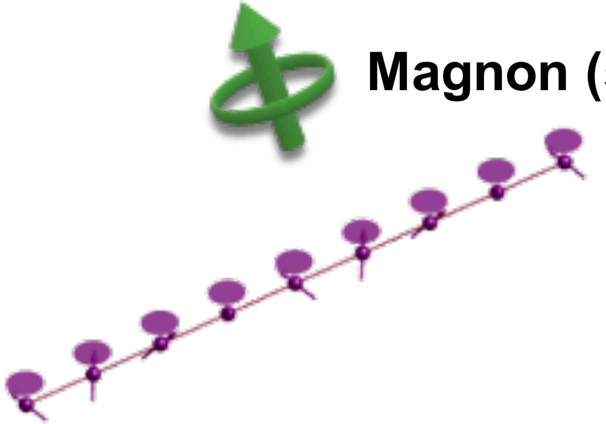
Experimental fact: an ideal triangular lattice is rather rare among magnetic systems.

Magnon-Phonon Coupling

PHYSICAL REVIEW VOLUME 110, NUMBER 4 MAY 15, 1958

Interaction of Spin Waves and Ultrasonic Waves in Ferromagnetic Crystals*

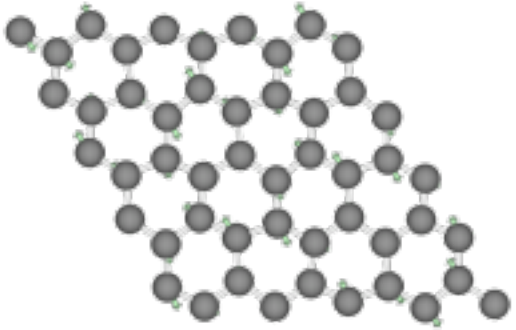
C. Kittel
Department of Physics, University of California, Berkeley, California
(Received January 9, 1958)



Magnon (spin waves)

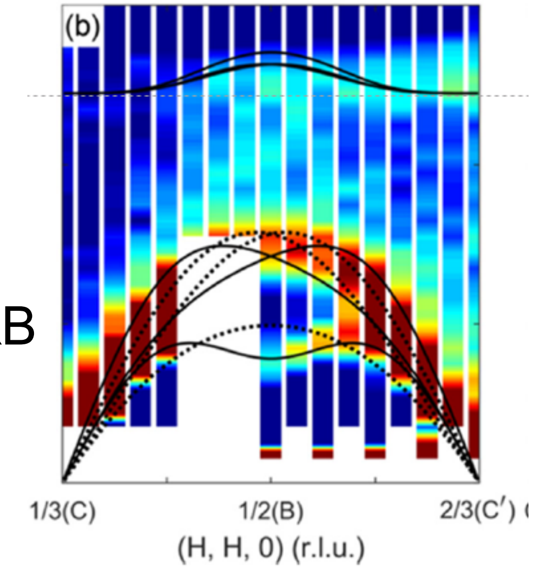
Magneto-elastic excitation

Phonon

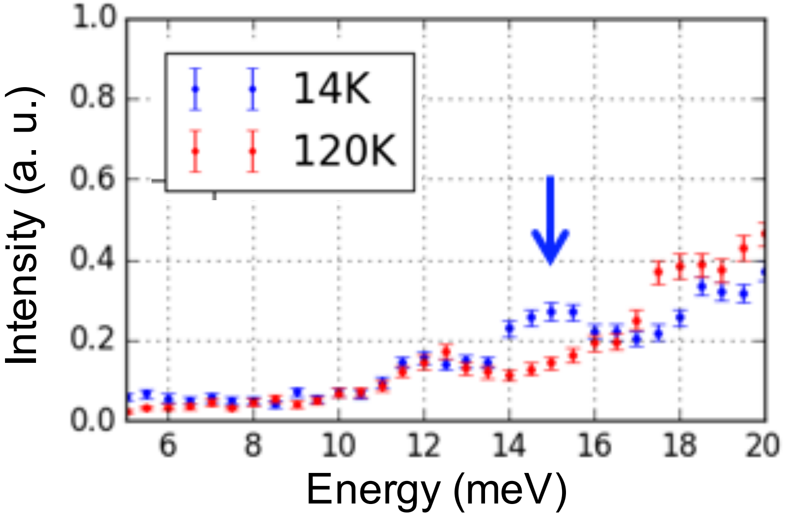


- ✓ Fundamental issue for magnetism
- ✓ Spintronics applicatons
- ✓ Thermoelectric materials
- ✓ Topological Physics: K. H. Lee et al., PRB (2018, 2019); H. R. Kim et al., to be published

Inelastic Neutron Scattering



Inelastic X-ray Scattering



K. Park, J-G. Park et al., PRB **94**, 104421 (2016)

Textbook Example: FeF_2

Diagonal components | Off-diagonal components

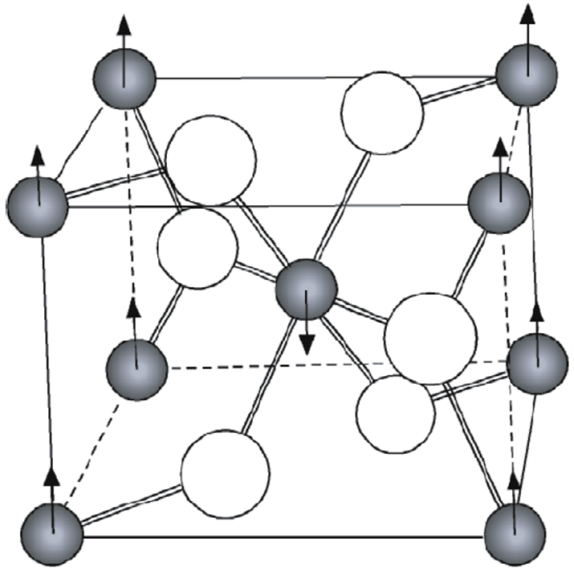
$$H_{mp} = U\left(\delta J \sum_{i,j,\alpha=x,y,z} \boldsymbol{S}_i \cdot \boldsymbol{S}_j + \delta D \sum_i (S_i^z)^2 + \delta K_1 \sum_{i,j,\alpha\neq\beta} S_i^\alpha S_j^\beta + \delta K_2 \sum_{i,\alpha\neq\beta} S_i^\alpha S_i^\beta\right)$$

1 phonon

Terms quadratic in S_i^x, S_i^y

Terms linear in S_i^x, S_i^y: 1 magnon

FeF_2



T. Chatterji et al., JPCM **22**, 316001 (2010)

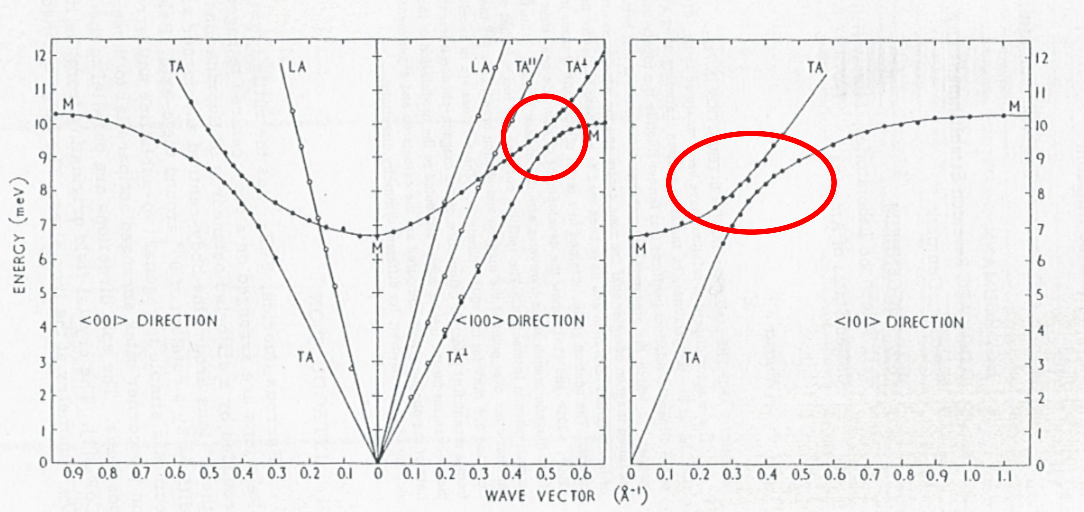


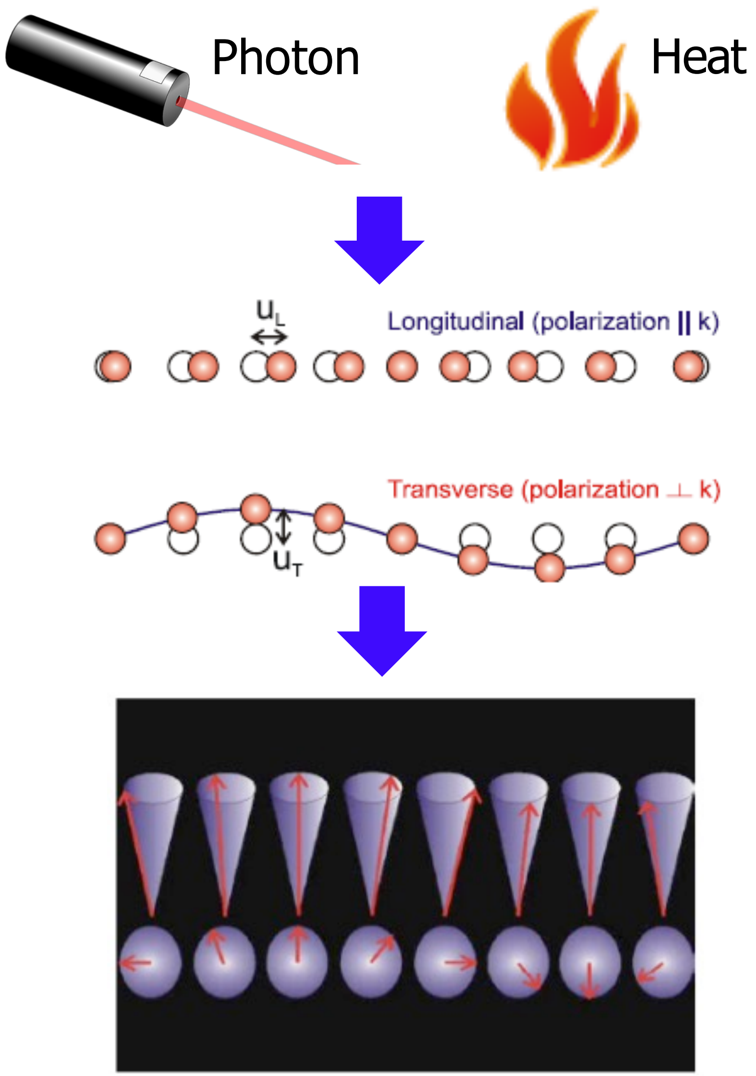
FIG. 1. Closed circles: dispersion relations measured around magnetic reciprocal lattice points at 4.2°K. M labels the magnon-like parts of the modes. Open circles: acoustic phonon dispersion measured at room temperature.

S. Lovesey, "Theory of Neutron Scattering from Condensed Matter systems," sect. 9.8

Magnon-Phonon for Spintronics

Spintronics: spins as data storage

Writing process by photon & heat



nature materials
LETTERS
PUBLISHED ONLINE: 21 AUGUST 2011 | DOI: 10.1038/NMAT3099

Long-range spin Seebeck effect and acoustic spin pumping

K. Uchida[1,2], H. Adachi[2,3], T. An[1,2], T. Ota[1,2], M. Toda[4], B. Hillebrands[5], S. Maekawa[2,3] and E. Saitoh[1,2,3,6]★

PNAS

Photodrive of magnetic bubbles via magnetoelastic waves

Naoki Ogawa[a,1], Wataru Koshibae[a], Aron Jonathan Beekman[a], Naoto Nagaosa[a,b], Masashi Kubota[a,c,2], Masashi Kawasaki[a,b], and Yoshinori Tokura[a,b]

[a]RIKEN Center for Emergent Matter Science, Wako, Saitama 351-0198, Japan; [b]Department of Applied Physics and Quantum Phase Electronics Center, University of Tokyo, Tokyo 113-8656, Japan; and [c]Research and Development Headquarters, ROHM Company, Ltd., Kyoto 615-8585, Japan

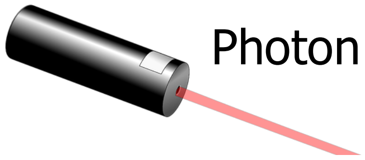
Edited by Chia-Ling Chien, The Johns Hopkins University, Baltimore, MD, and accepted by the Editorial Board June 6, 2015 (received for review February 27, 2015)

- Magnon-phonon coupling is important for spin conversion.
- Conversion factor $\propto$ coupling strength

Magnon-Phonon in YIG

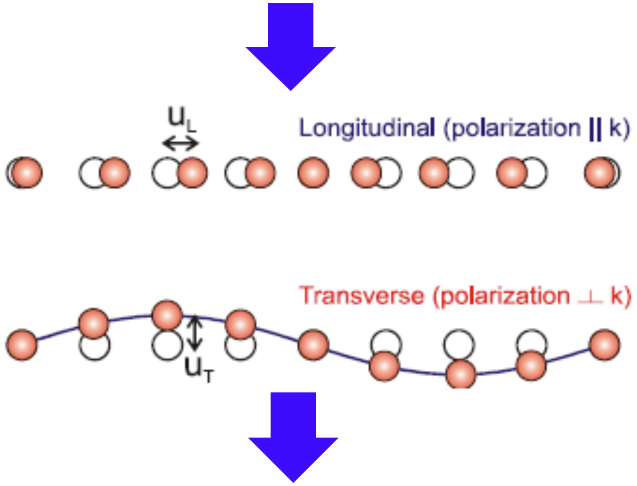
Spintronics: spins as data storage

Writing process by photons & heat



Photon

Heat



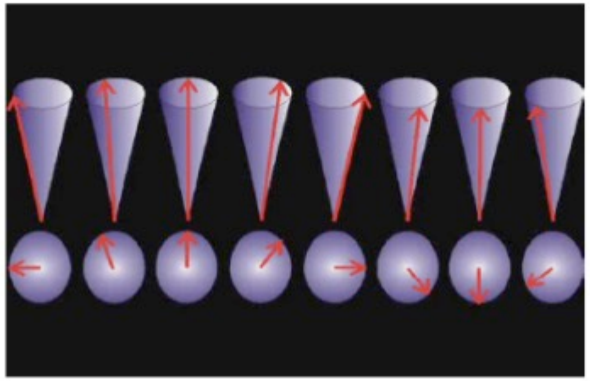
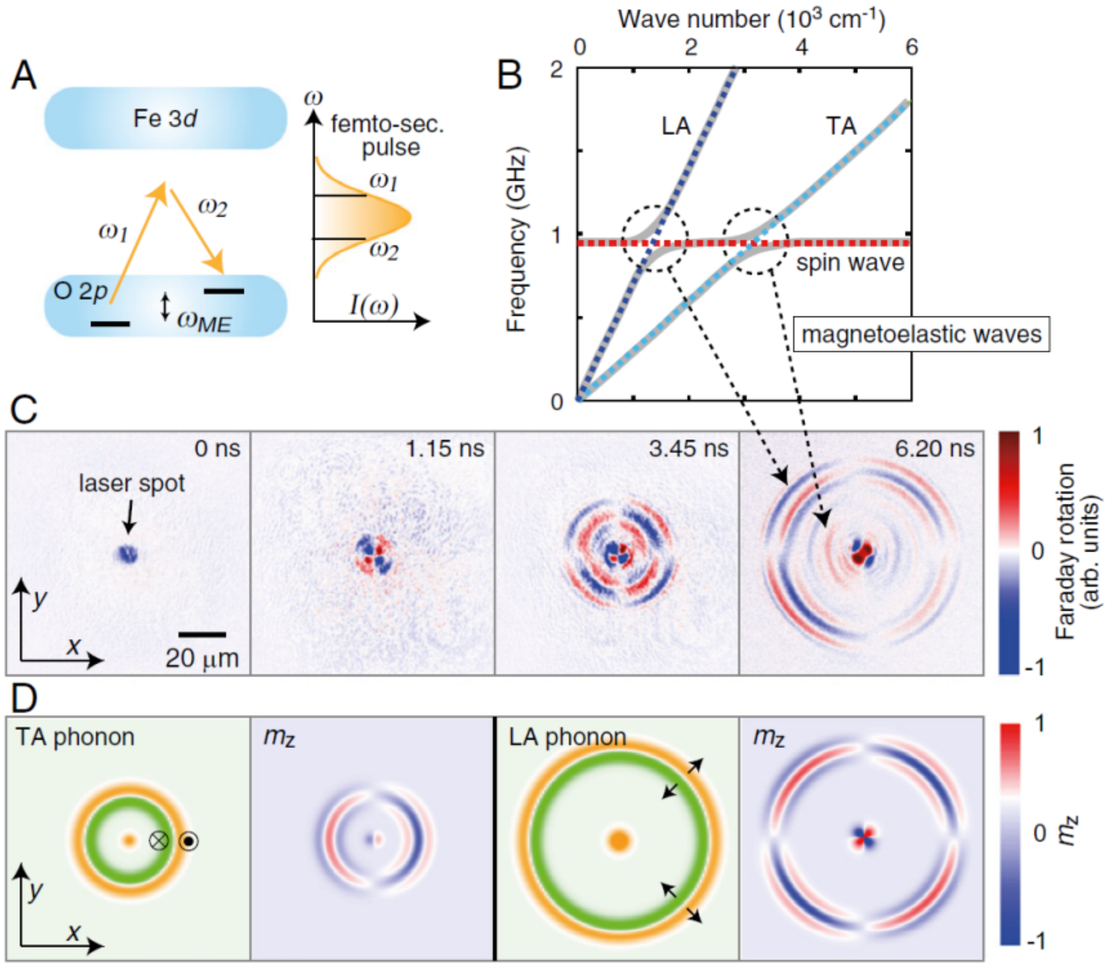
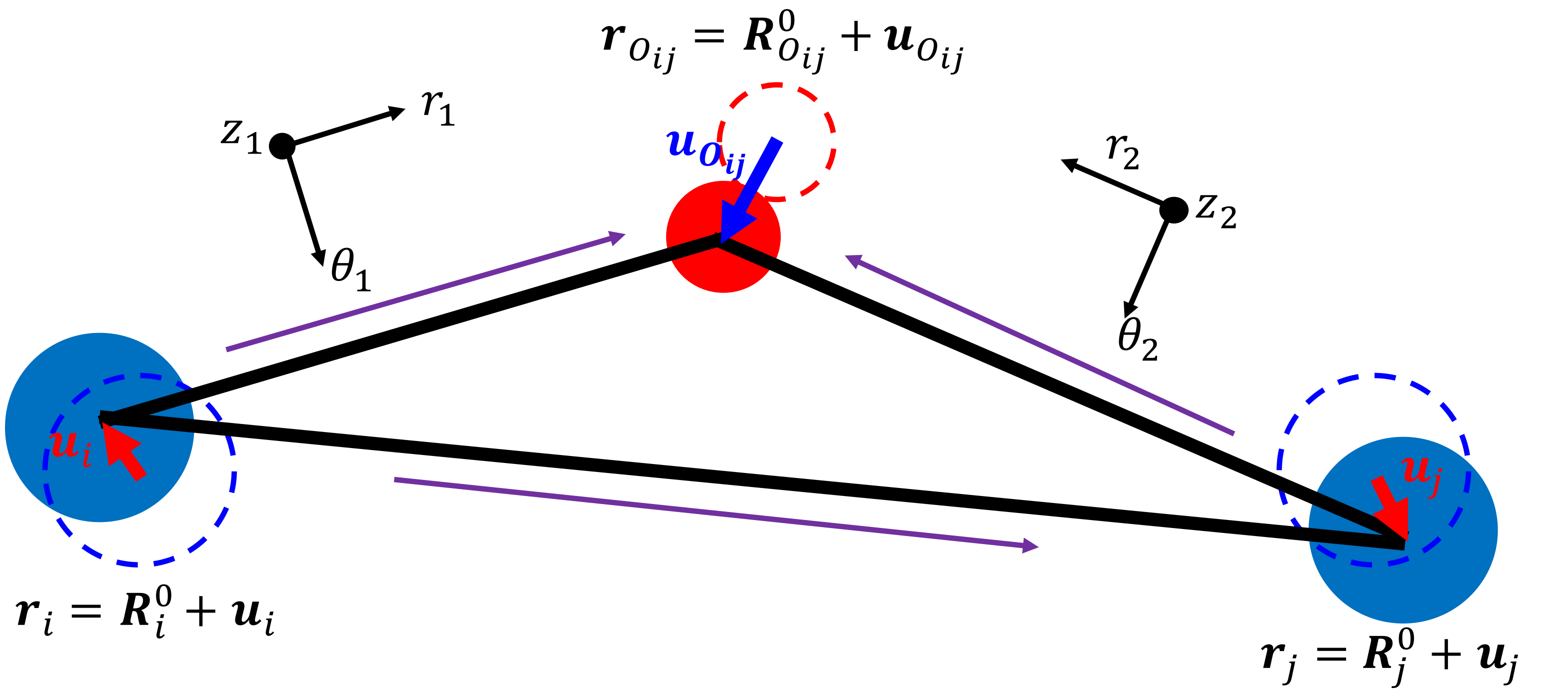


Photo-induced magnetic domain in YIG



N. Ogawa et al., PNAS 112, 8977 (2015)

Magnon-Phonon coupling: exchange-striction



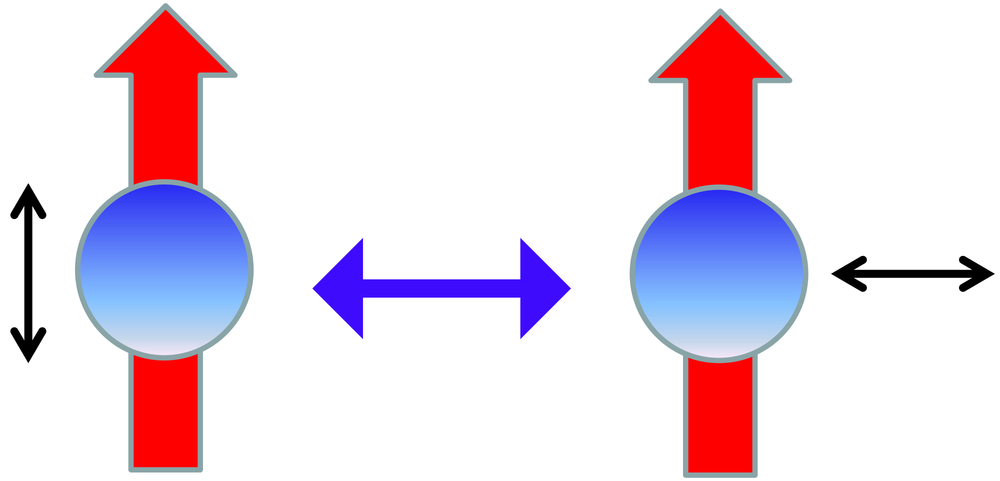
$$H = H_{Heis} + H_{lattice} = \sum_{ij} J_{ij}\boldsymbol{S}_i \cdot \boldsymbol{S}_j + H_{lattice}$$

$$J_{ij}\left(\boldsymbol{R}_i, \boldsymbol{R}_j, \boldsymbol{R}_{O_{ij}}\right) = J_0 + (\boldsymbol{u}_1 \cdot \nabla_1 + \boldsymbol{u}_2 \cdot \nabla_2 + \boldsymbol{u}_3 \cdot \nabla_3)J_{ij} + \cdots$$

$$(\boldsymbol{u}_1 \cdot \nabla_1 + \boldsymbol{u}_2 \cdot \nabla_2 + \boldsymbol{u}_3 \cdot \nabla_3)J_{ij} = \underbrace{\left(\boldsymbol{u}_{O_{ij}} - \boldsymbol{u}_i\right) \cdot \nabla_1(J_{ij}) + \left(\boldsymbol{u}_{O_{ij}} - \boldsymbol{u}_j\right) \cdot \nabla_2(J_{ij})}_{\text{Superexchange-striction}} + \underbrace{\left(\boldsymbol{u}_j - \boldsymbol{u}_i\right) \cdot \nabla_3(J_{ij})}_{\text{Direct exchange-striction}}$$

Magnon-Phonon coupling: exchange-striction

- Exchange energy is dominant in most 3d TM based magnets
- No linear coupling in collinear spin structure



Longitudinal spin fluctuation

$S_i^z = S - b_i^\dagger b_i$

Transverse spin fluctuation

$S_i^x, S_i^y = b_i^\dagger, b_i$

$$H = J \sum_{i,j} \boldsymbol{S_i} \cdot \boldsymbol{S_j}$$

$$= J \sum_{i,j} \left(S_i^x S_j^x + S_i^y S_j^y + S_i^z S_j^z \right)$$

$$H_{mp} = U \delta J S \sum_{i,j} \left(S_i^x S_j^x + S_i^y S_j^y + S_i^z S_j^z \right)$$

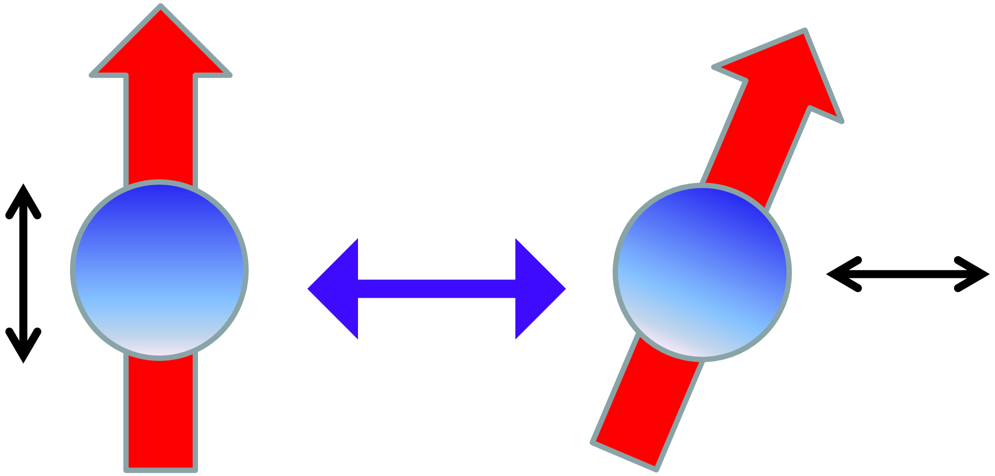
1 phonon

2 magnon

Magnon-Phonon coupling via exchange-striction

- Noncollinear magnetic structure: Transverse-longitudinal coupling
  → Direct mixing of magnons and phonons

Joosung Oh
PhD Thesis
(2017)



Longitudinal spin fluctuation

$S_i^z = S - b_i^\dagger b_i$

Transverse spin fluctuation

$S_i^x, S_i^y = b_i^\dagger, b_i$

$$H = J \sum_{i,j} \boldsymbol{S}_i \cdot \boldsymbol{S}_j$$

$$= JS \sum_{i,j} \left(S_i^x + S_i^y + \cdots \right)$$

$$H_{mp} = U \delta JS \sum_{i,j} \left(S_i^x + S_i^y + \cdots \right)$$

1 phonon (U)

1 magnon ($S_i^x + S_i^y + \cdots$)

Calculation of Hybrid ME Excitations

- Lattice & spin modulation → phonon & magnon operators
- Numerical diagonalization of Hamiltonian
- Calculation of dynamical spin structure factor

Joosung Oh
PhD Thesis
(2017)

$$H = H_{spin} + \hbar \sum_{i=1}^{90} \omega_i b_k^\dagger b_k + \frac{\alpha J}{2d} \sum_{ij} \left(\boldsymbol{e}_{O_{ij}i} \cdot \boldsymbol{U}_i + \boldsymbol{e}_{O_{ij}j} \cdot \boldsymbol{U}_j \right) \boldsymbol{S}_i \cdot \boldsymbol{S}_j$$

Lattice modulation: $\boldsymbol{U}_{j,l} = \sqrt{\frac{\hbar}{2Nm_j\omega_{k\lambda}}} \sum_{k,\lambda} \boldsymbol{V}_{j,k\lambda} e^{ik\cdot(R_l + r_j)} \left(b_{k\lambda} + b^\dagger_{-k\lambda} \right)$

Spin modulation: $\boldsymbol{S}_i^- \simeq \sqrt{2S} a_i^\dagger$

Matrix from: $H = S \sum_k X^\dagger_{tot} \begin{pmatrix} L & -iN^\dagger & M & -iN^\dagger \\ iN & \Omega & -iN & 0 \\ M & iN^\dagger & L & -iN^\dagger \\ iN & 0 & iN & \Omega \end{pmatrix} X_{tot}$

Spin

Coupling

Phonon

$$X_{tot} = \left(a_{k1} \cdots a_{k6}\ b_{k1} \cdots b_{k\lambda} \cdots a^\dagger_{-k1} \cdots a^\dagger_{-k6}\ b^\dagger_{-k1} \cdots b^\dagger_{-k\lambda} \cdots \right)^T$$

magnon   phonon

Estimated α For $YMnO_3$

$$\alpha = \frac{d(P_0)\,\partial T_N/\partial P}{T_N(P_0)(\partial d/\partial P)} = 14$$

- T. Lancaster et al., PRL 98, 197203 (2007)
- D. P. Kozlenko, JGP et al., JETP 82, 193 (2005)

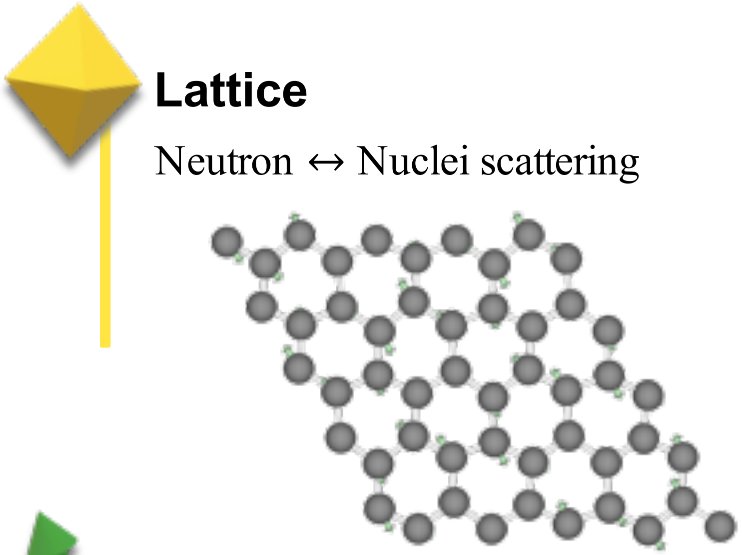
La_2CuO_4: $\alpha = 6 \sim 7$

$CuCrO_2$: $\alpha = 30$

- M. C. Aronson et al., PRB 44, 4657 (1991)
- K. Park, JGP et al., PRB 94, 104421 (2016)

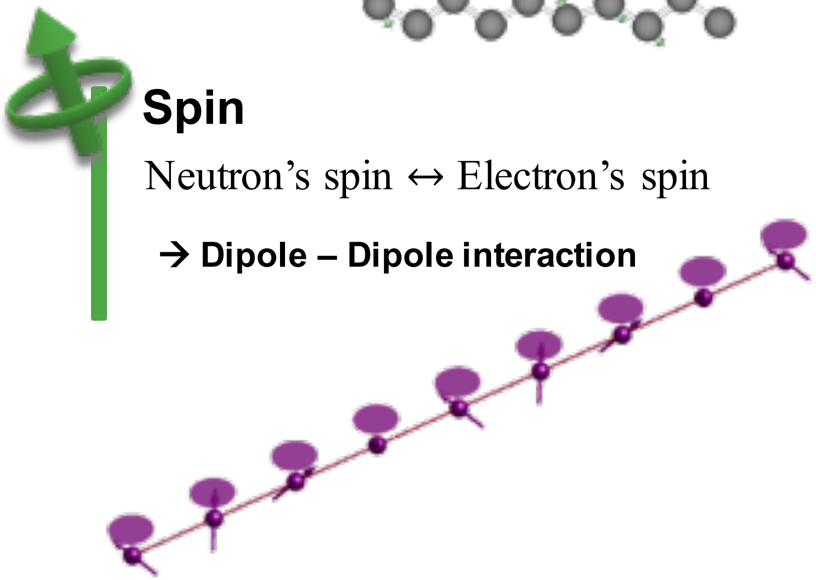
Two Experimental Tools

Inelastic Neutron Scattering



Lattice

Neutron ↔ Nuclei scattering

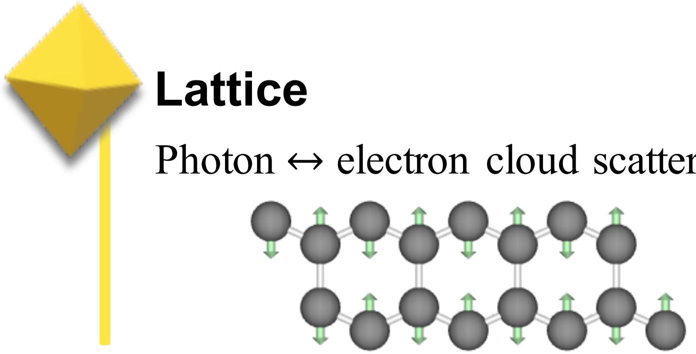


Spin

Neutron's spin ↔ Electron's spin

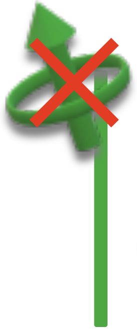
→ **Dipole – Dipole interaction**

Inelastic X-ray Scattering

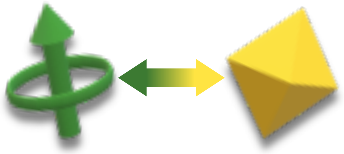


Lattice

Photon ↔ electron cloud scattering



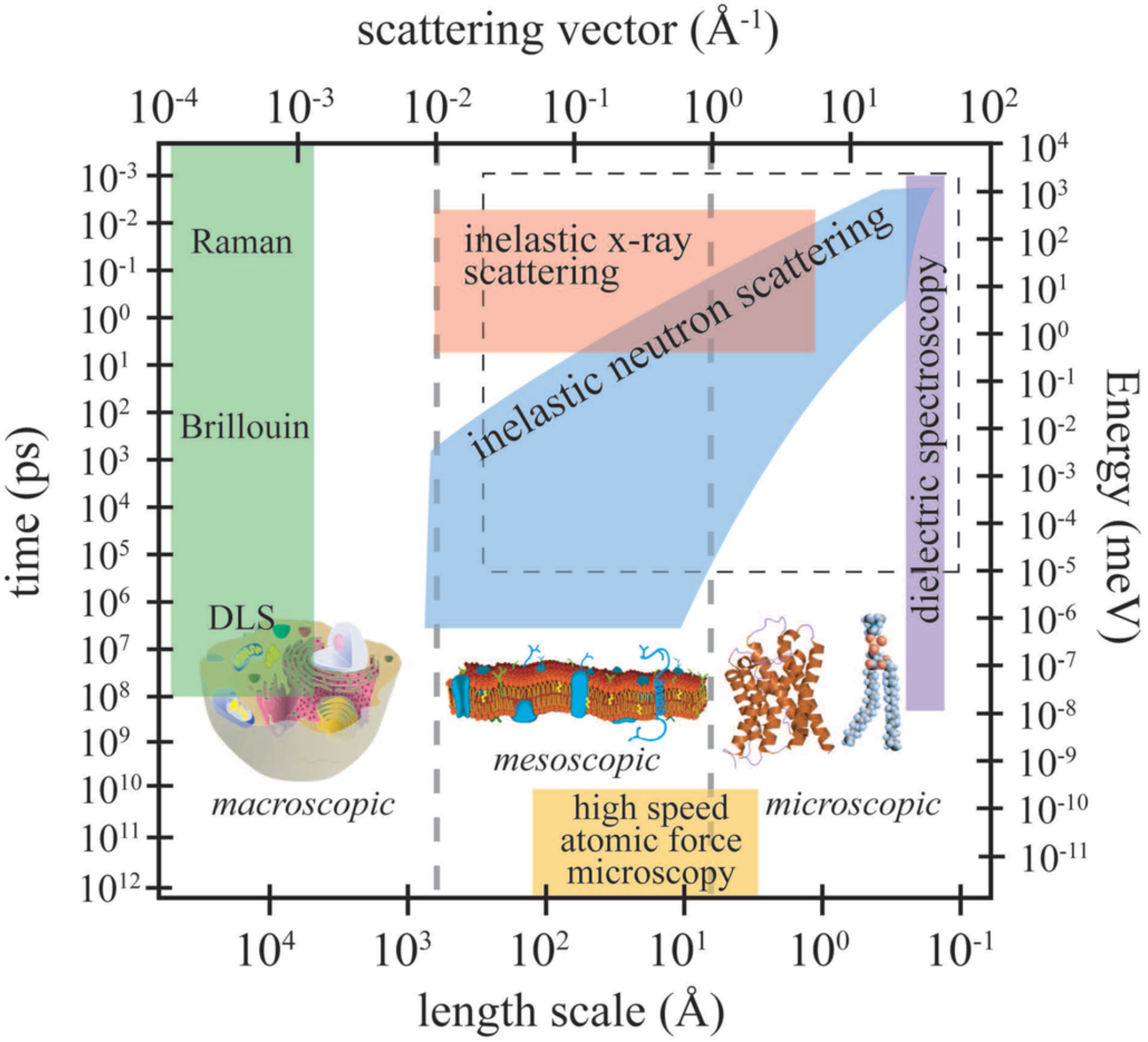
(Photons cannot detect spin, but…)



Spin-Lattice coupling

IXS can probe magneto-elastic excitation indirectly.

Inelastic Neutron vs Inelastic X-Ray Scattering



- **Wavelengths** of neutrons and x-ray are similar to atomic spacing!
- **Energy** of neutrons and x-ray are similar to elementary excitations in solids!

Advantage of Inelastic neutron scattering

- Probes both spin & lattice excitation
- Good energy resolution
- Sensitive to light atoms

Advantage of Inelastic x-ray scattering

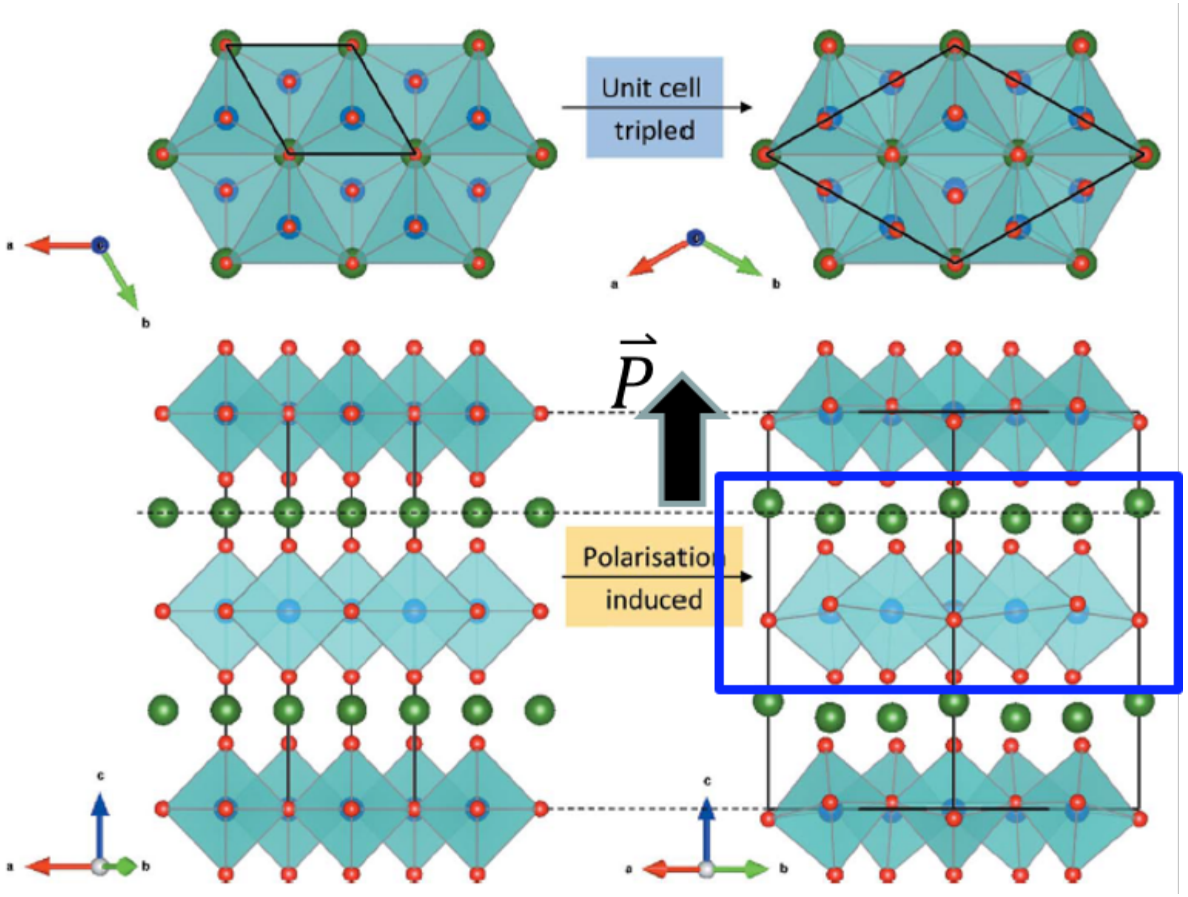
- Probes lattice vibration
- Good momentum resolution
- Low background
- Small sample down to 10μm and 100nm film

Magnon-Magnon/Phonon Coupling in hexagonal Manganites

Inelastic Neutron and X-ray Scattering

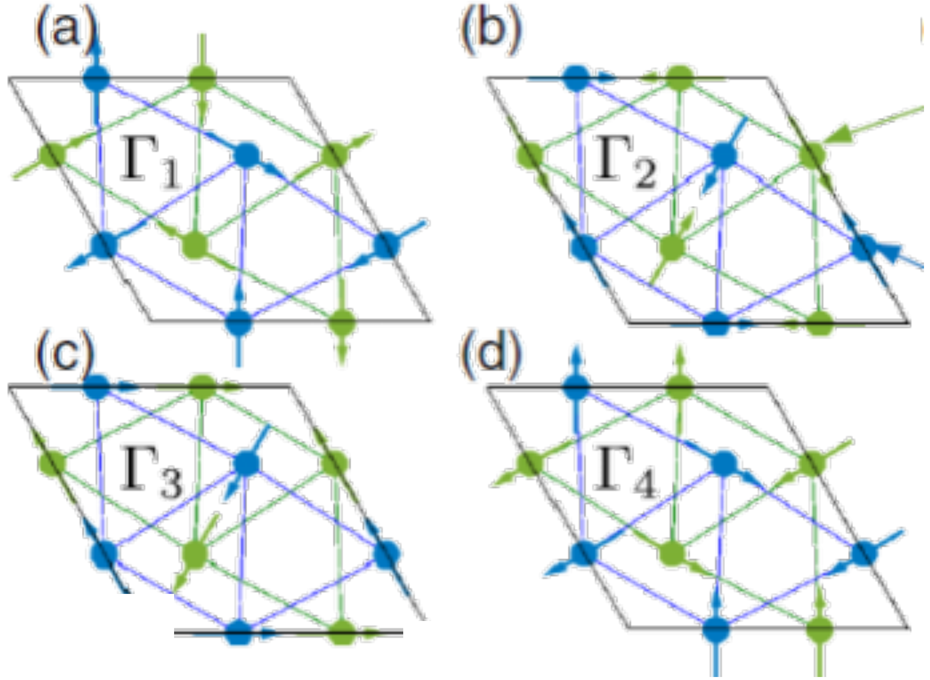
2D Triangular Antiferromagnet $(Y,Lu)MnO_3$

- Structural transition from paraelectric ($P6_3/mmc$) to ferroelectric ($P6_3cm$) below T_c~1250 K
- Mn atoms form triangular layers
- 120° noncollinear magnetic order below T_N due to geometrical frustration



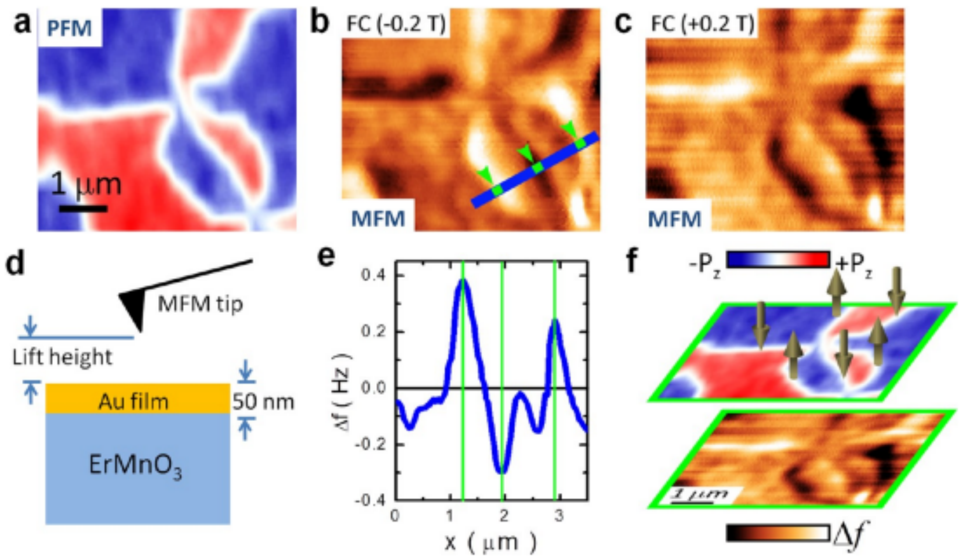
- $YMnO_3$: T_N=75 K, θ_{CW}=705 K
- $LuMnO_3$: T_N=90 K, θ_{CW}=887 K

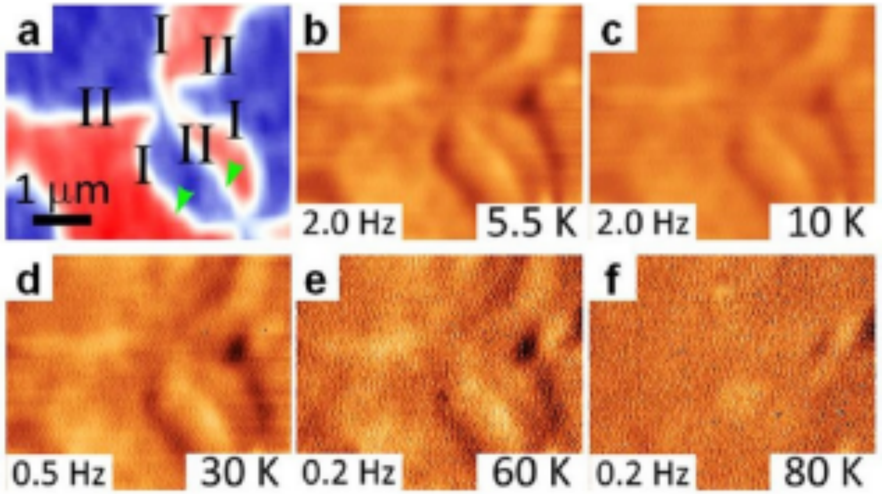
4 possible magnetic structure of $P6_3cm$ space group



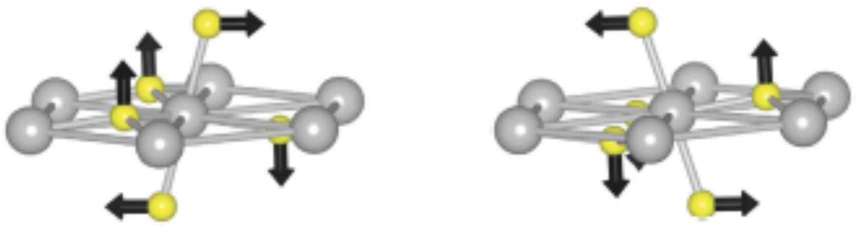
H. Sim, J-G. Park et al., Acta Cryst. B**72**, 1 (2016)

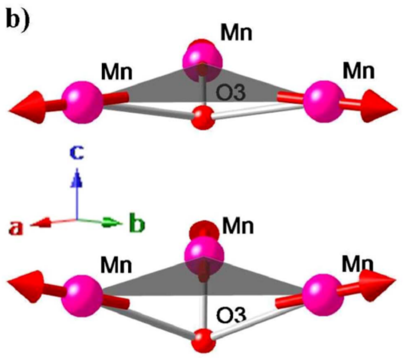
Ferroelectric-Magnetic domain locking

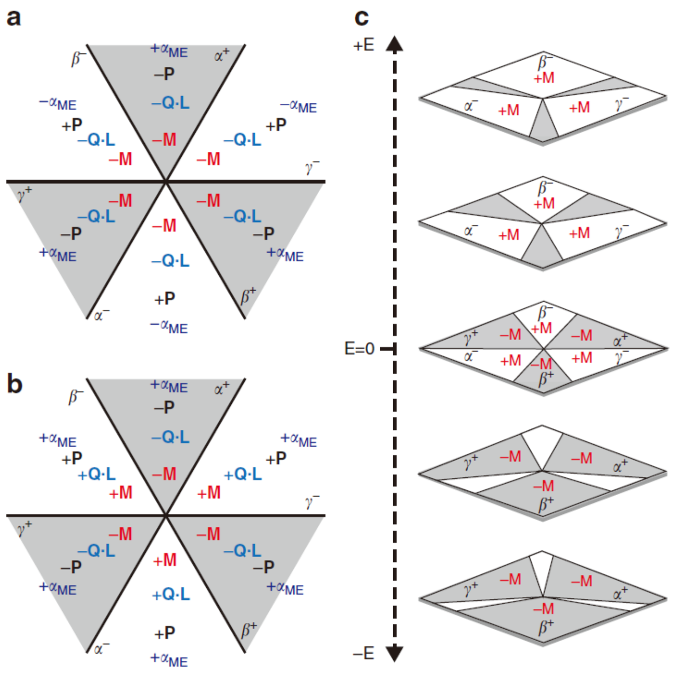


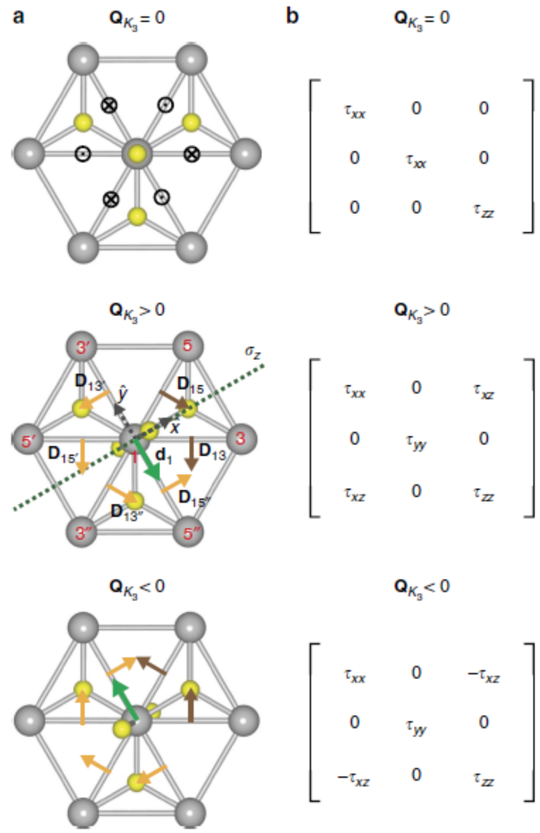


Q_{K_3} phonon mode (Ferroelectric transition)





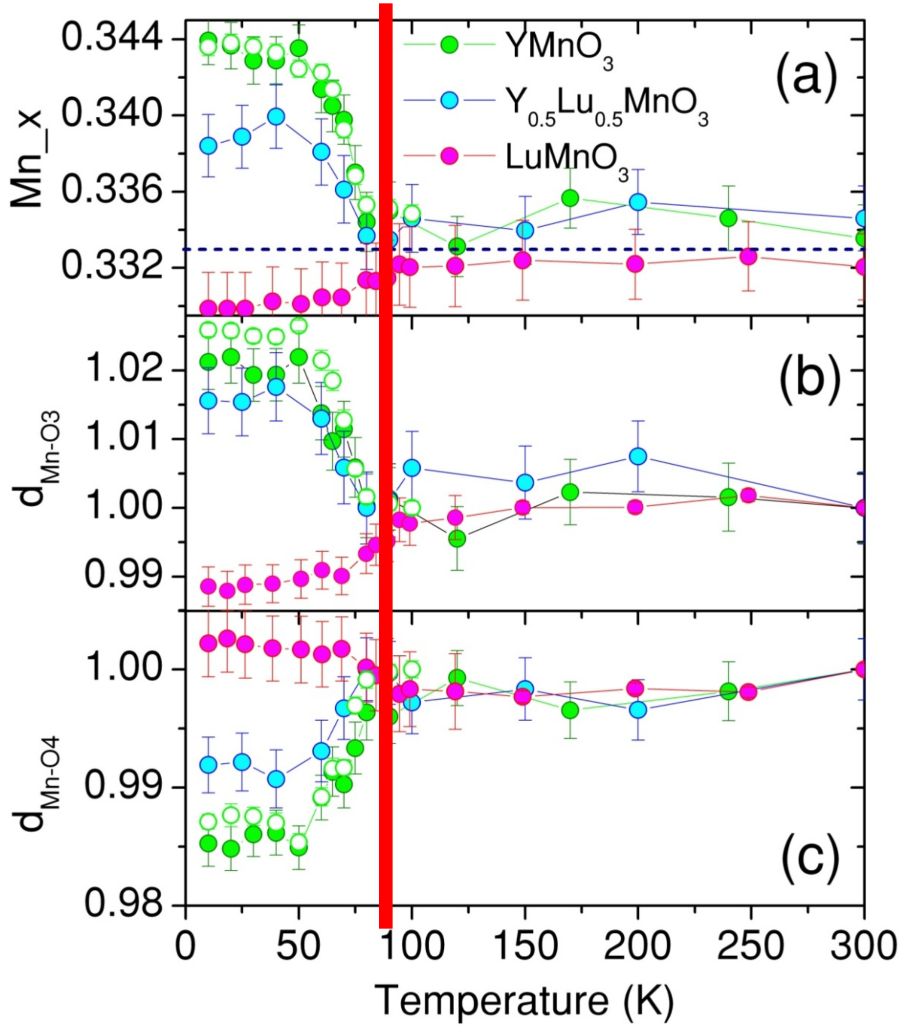


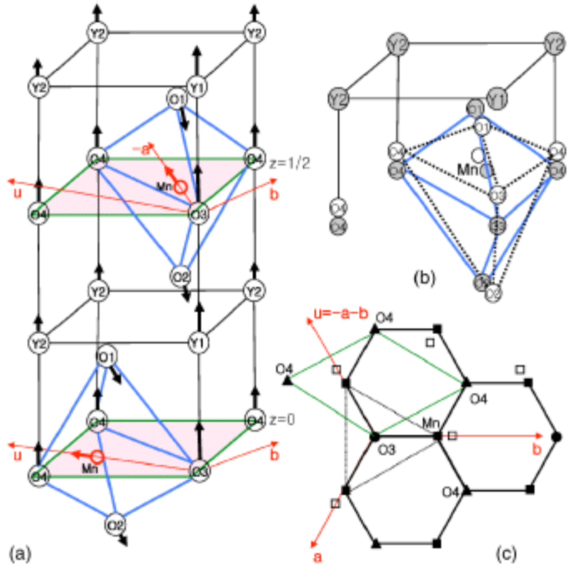


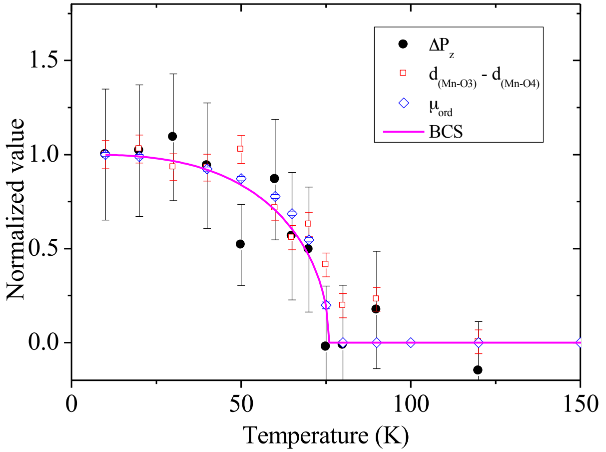
Several papers from S-W Cheong's group
Y. Geng et al., Nano Lett., 12, 6055 (2012)
H. Das et al., Nat. Commun. 5, 2998 (2014)

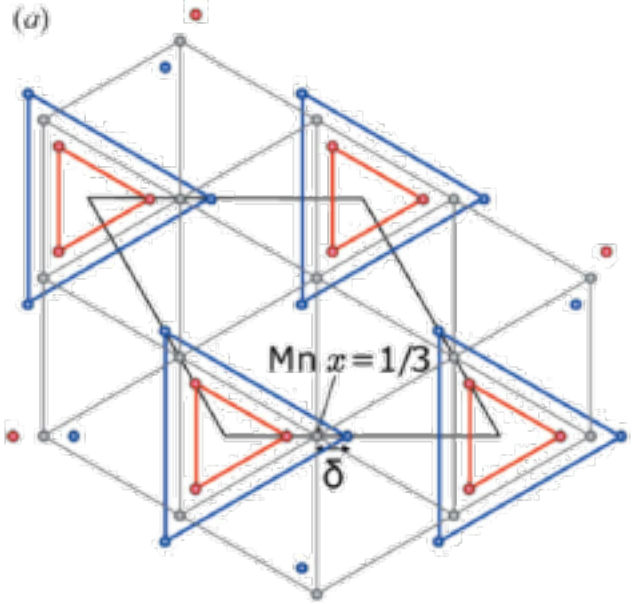
Spin-Lattice Coupling in h-$RMnO_3$

- Atomic displacement below T_N
- Large displacement of Mn x position induces Mn trimerization.









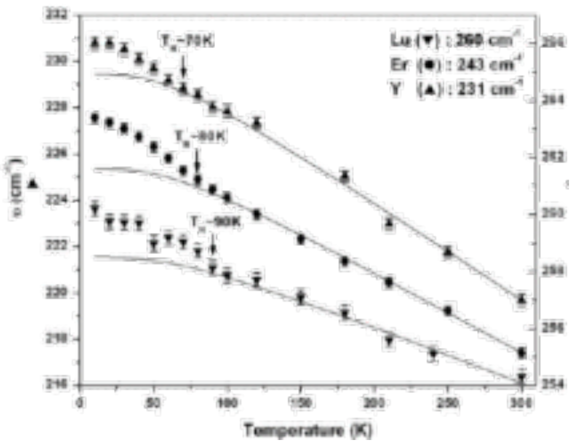
$$\Delta\vec{P}(T) = \sum_i q_i(\vec{r_i}(T) - \vec{r_i}(300K)),$$

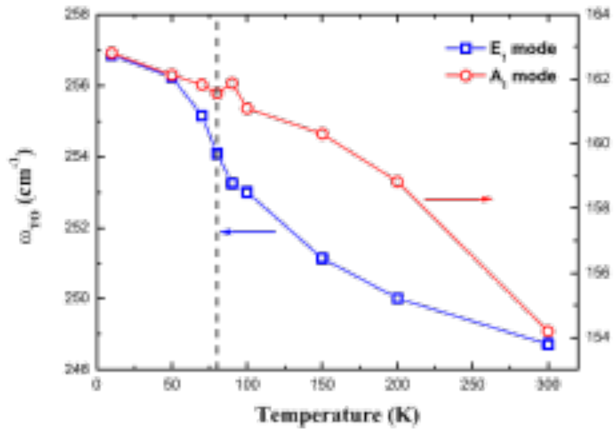
S. Lee, JGP et al., PRB (2005)
S. Lee, JGP et al., Nature (2008)

Spin-Lattice Coupling in h-$RMnO_3$

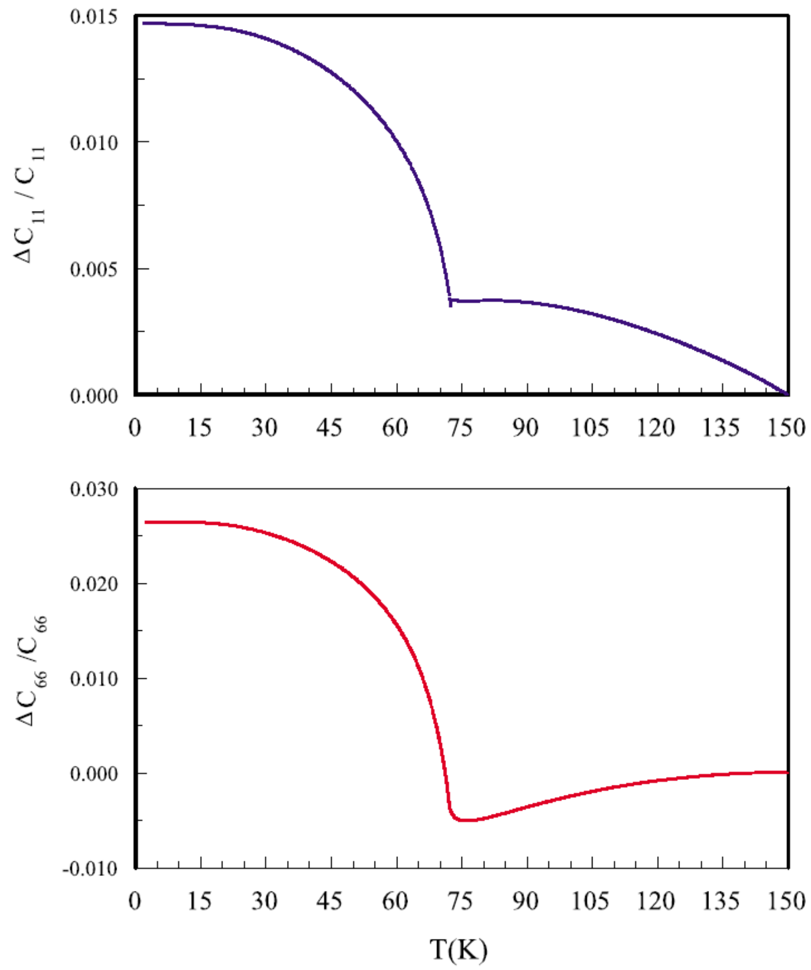
- Numerous evidences of spin-lattice(phonon) coupling in $YMnO_3$

Phonon anomaly

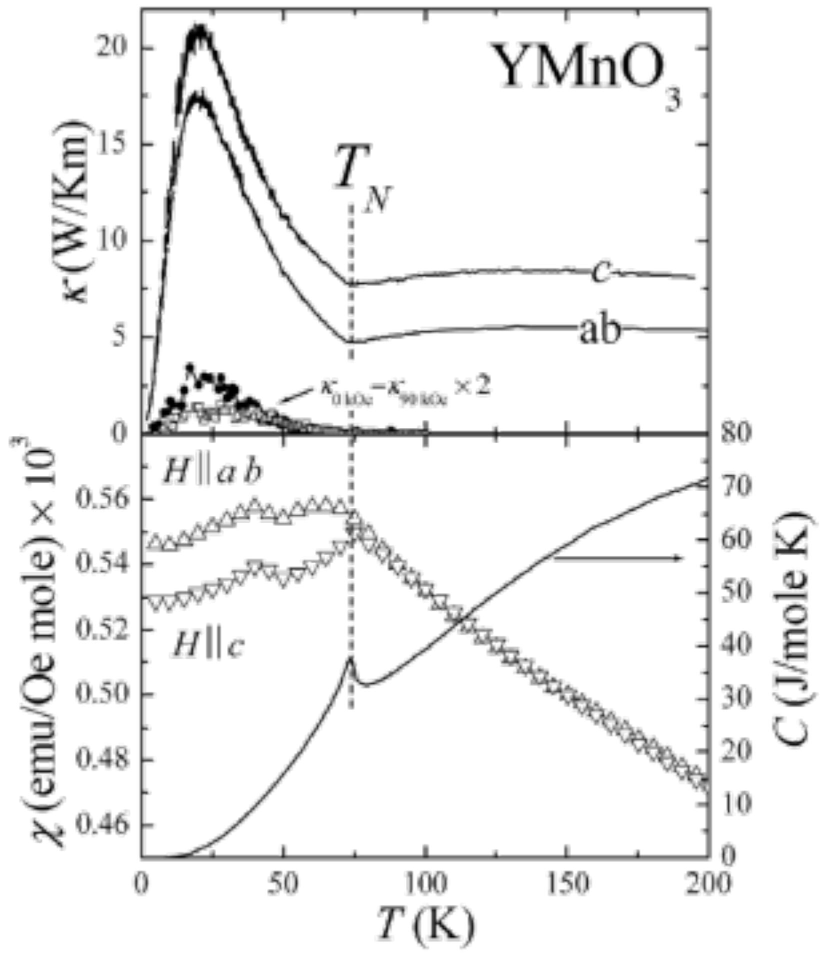




Elastic moduli



Thermal conductivity



M. N. Iliev et al., PRB **56**, 2488 (1997)
P. A. Sharma et al., PRL **93**, 177202 (2004)
M. Poirier et al., PRB **76**, 174426 (2007)

Magnon dispersion relation

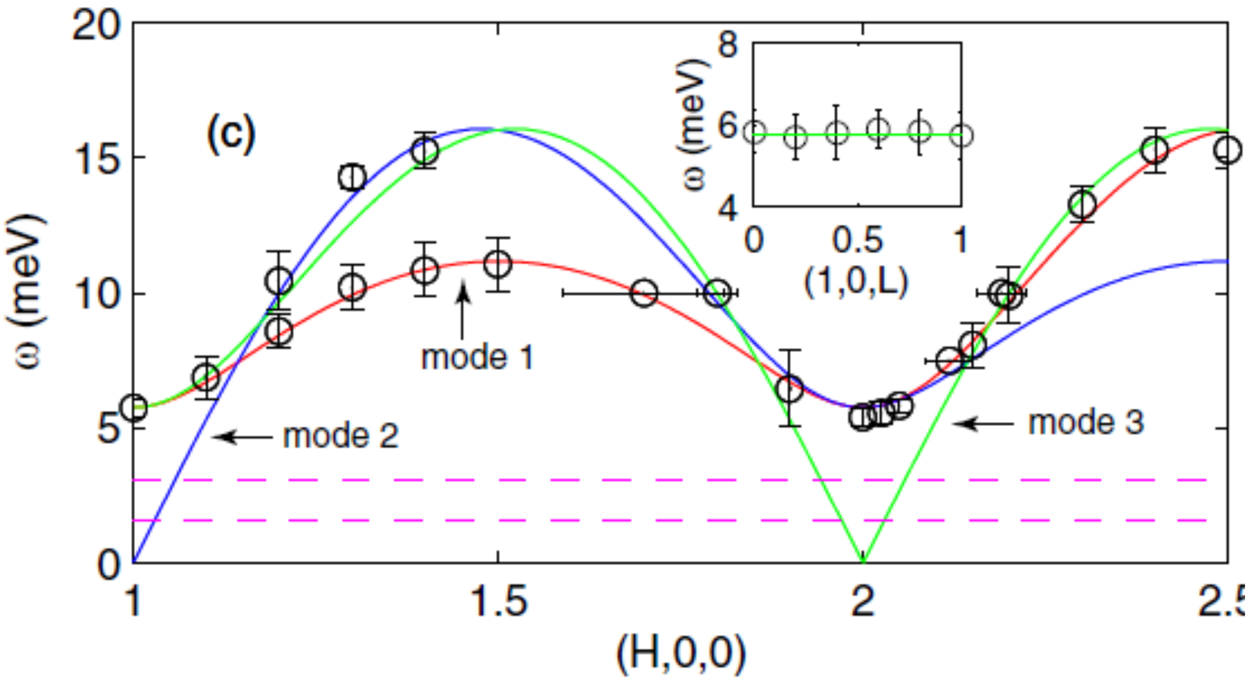
- Three magnon modes
- J=2.5 meV, D=0.28 meV

Spin Hamiltonian

$$H_{ex} = J\sum S_r \cdot S_{r+\delta} \;+ D \sum_r (S_r^z)^2$$

Antiferro
J >0

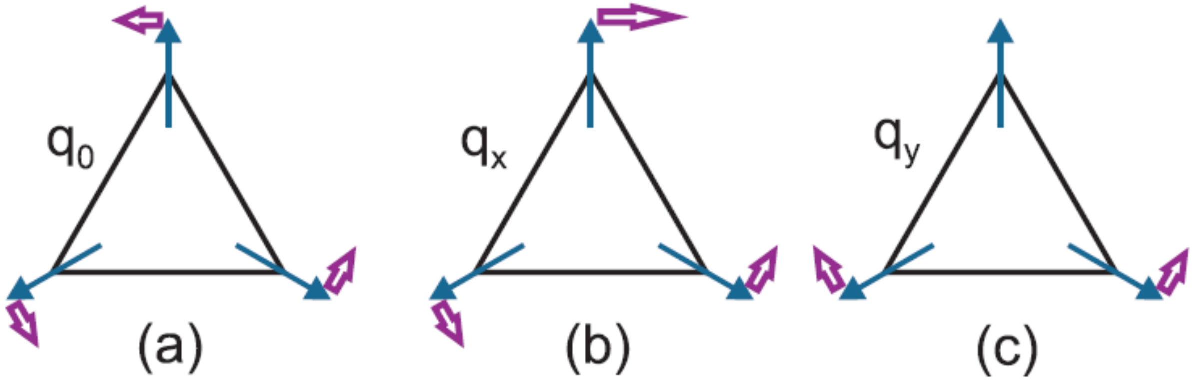
Easy plane
D1>0



O. P. Vajk *et al.*, PRL **94**, 087601 (2005)

Phason mode
(mode 1)

Spin canting modes
(mode 2,3)

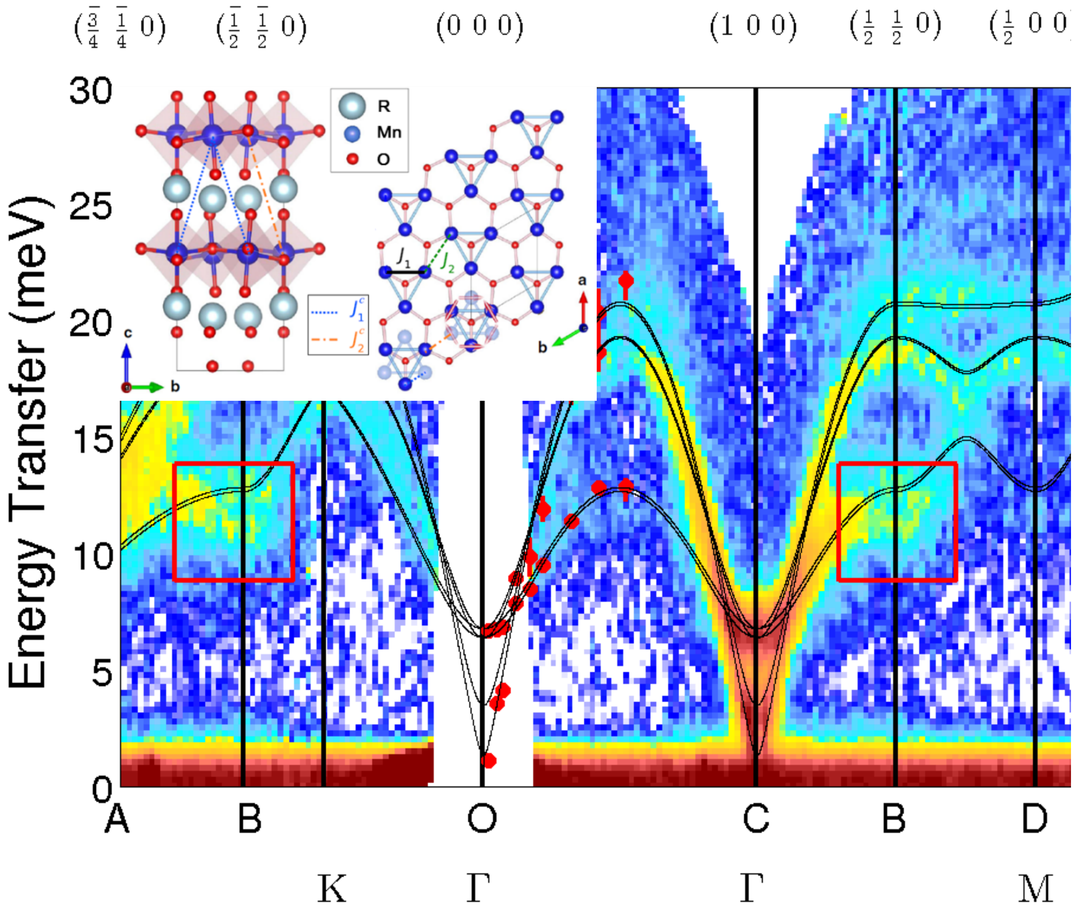


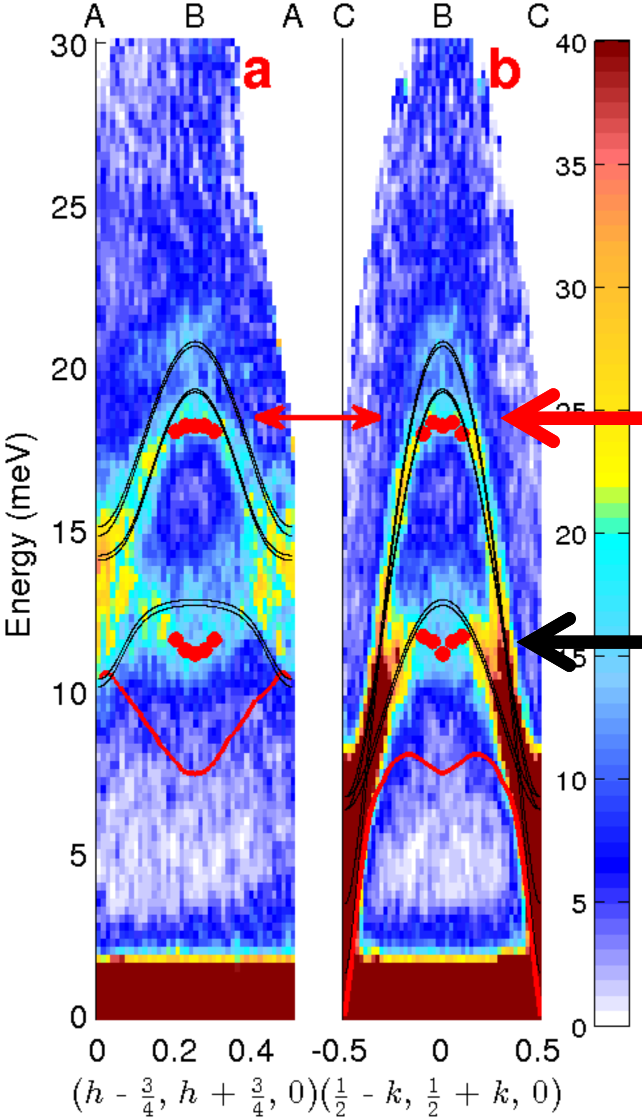
M. A. van der Varte et al., arXiv:0907.3055

Magnon-Magnon coupling in $LuMnO_3$

$$H = -J_1 \sum_{\text{intra}} \vec{S_i}\vec{S_j} - J_2 \sum_{\text{inter}} \vec{S_i}\vec{S_j} - J_1' \sum_{\text{out intra}} \vec{S_i}\vec{S_j} - J_2' \sum_{\text{out inter}} \vec{S_i}\vec{S_j} - J_3 \sum_{\text{next nn}} \vec{S_i}\vec{S_j} - D_1 \sum (S_i^z)^2 - D_2 \sum (\vec{n}\cdot\vec{S_i})^2$$

J_1=-9 meV, J_2=-1.4 meV, J_3=0 meV, J_1'=-0.018 meV





J. Oh, JGP et al., PRL 111, 257202 (2013)
selected as Editor's suggestion of PRL

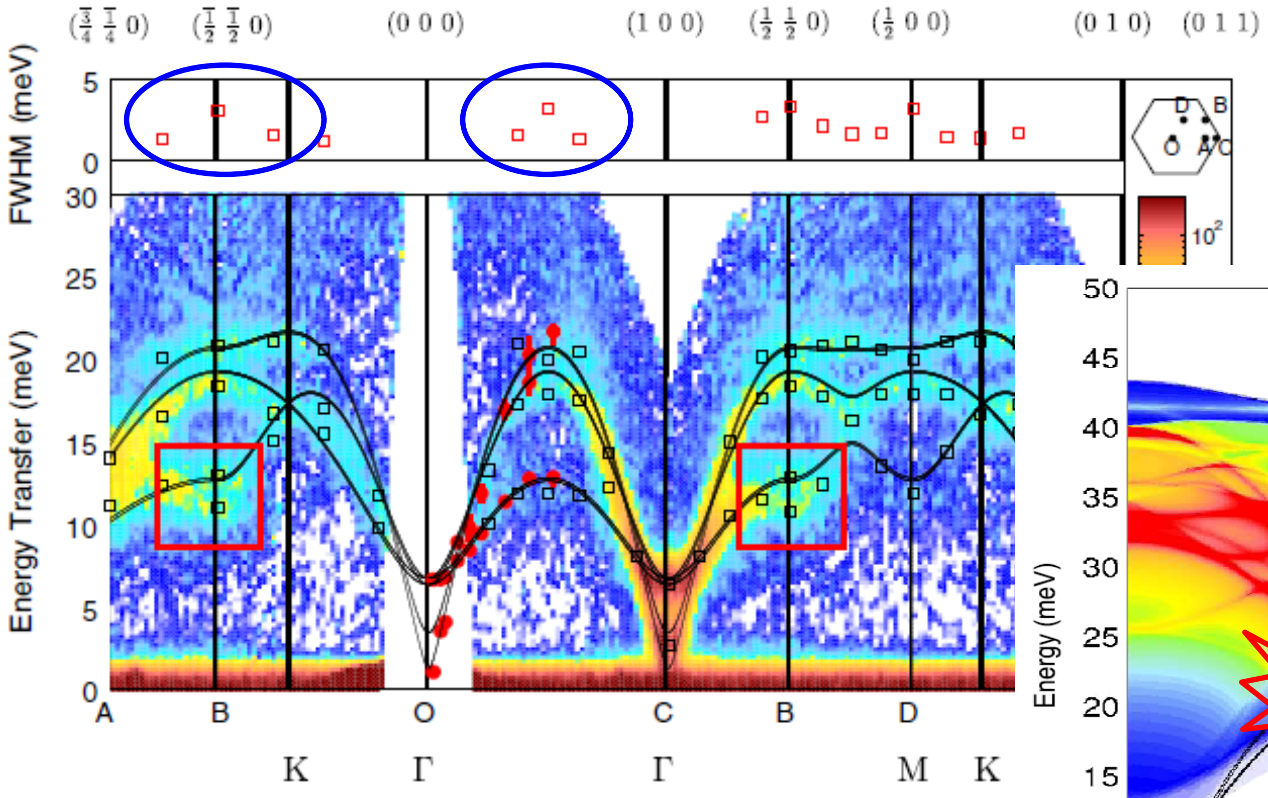
Flat mode

Roton-like minimum

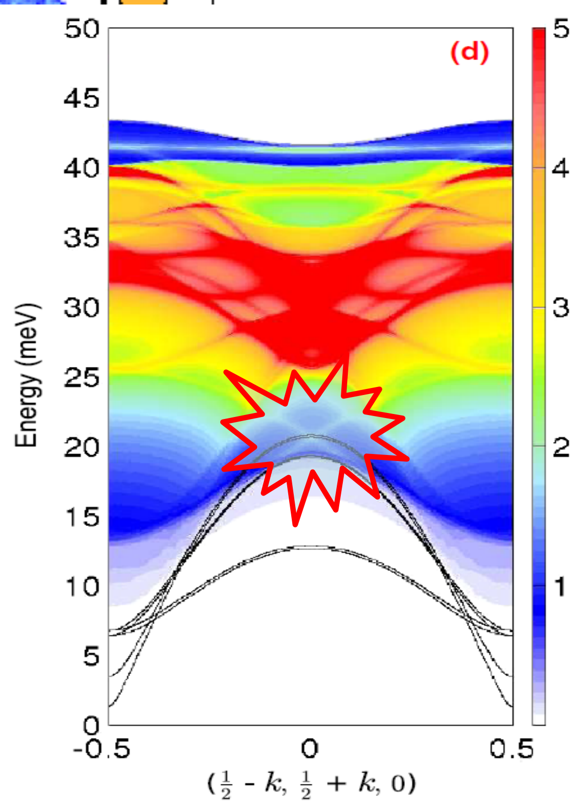
Linewidth Broadening in $LuMnO_3$

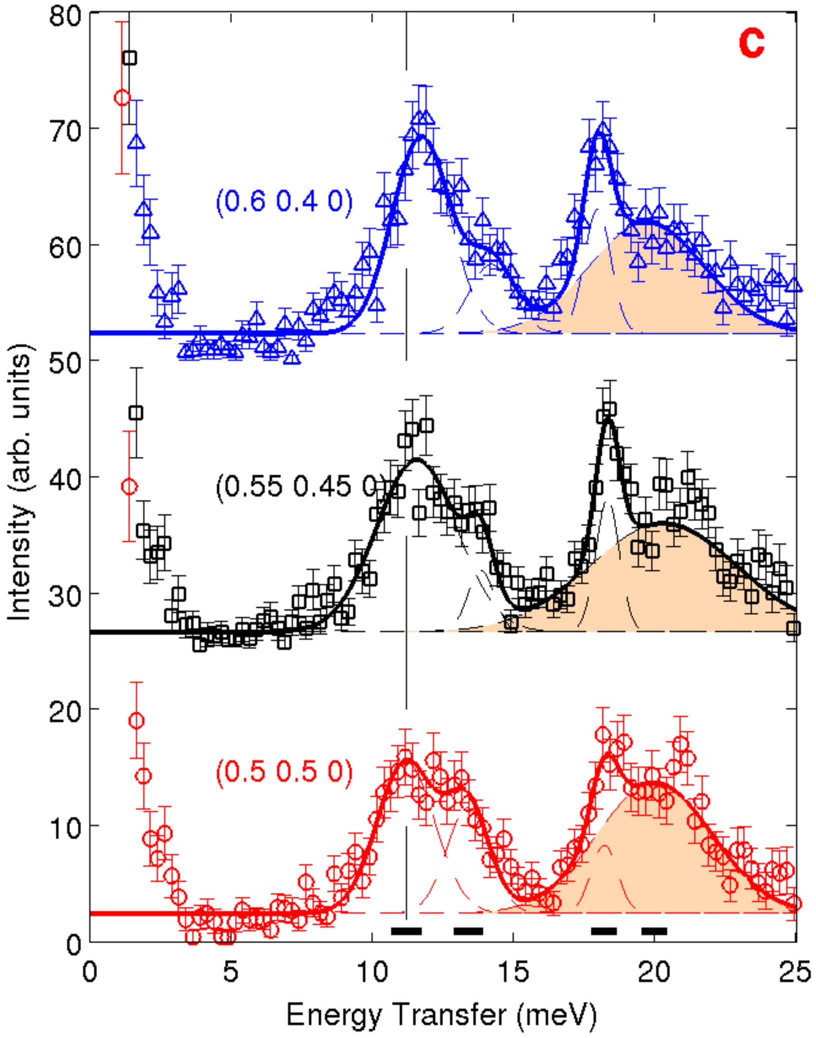
J. Oh, JGP et al., PRL 111, 257202 (2013)
selected as Editor's suggestion of PRL

Observation of linewidth broadening in $LuMnO_3$



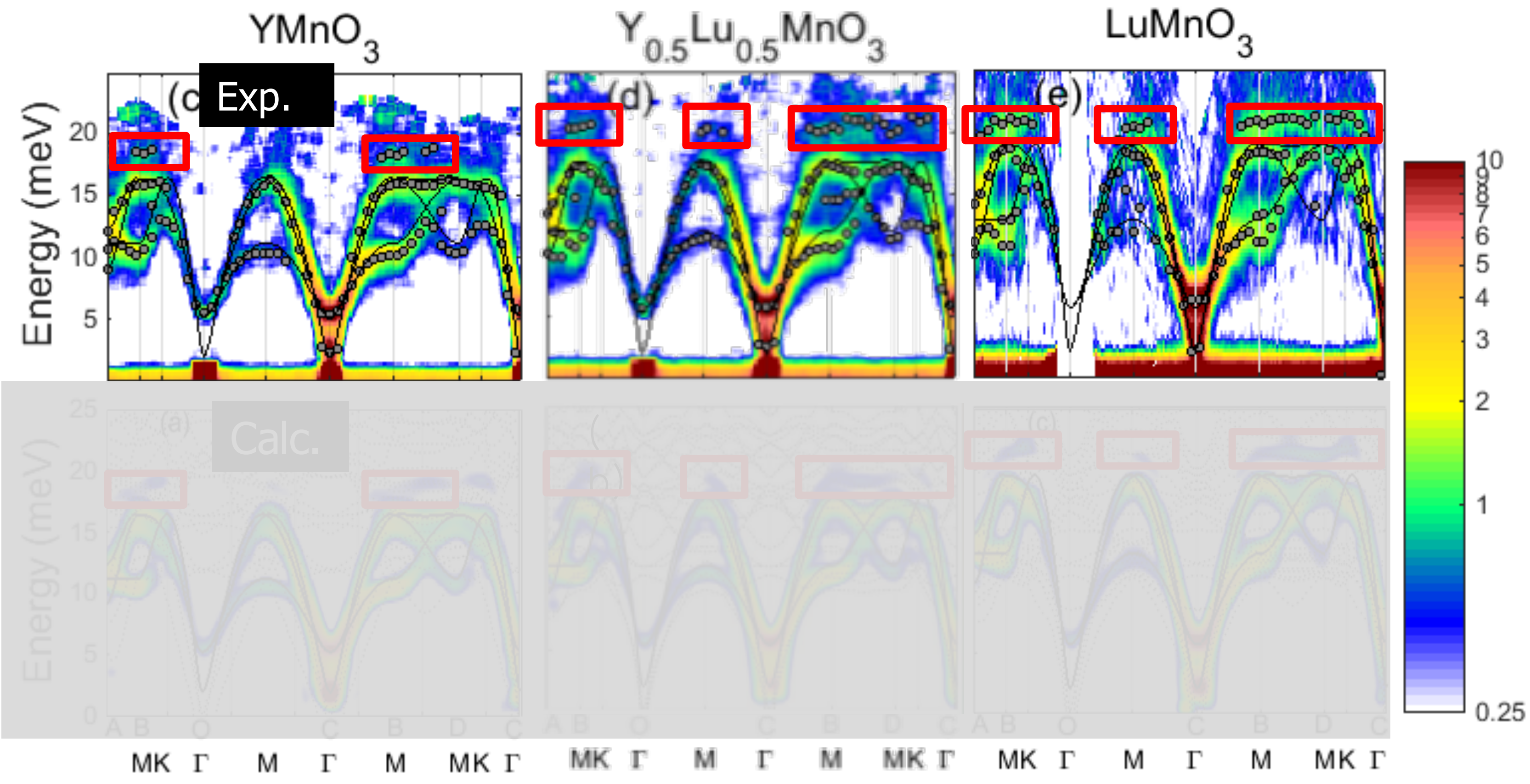
Two magnons DOS

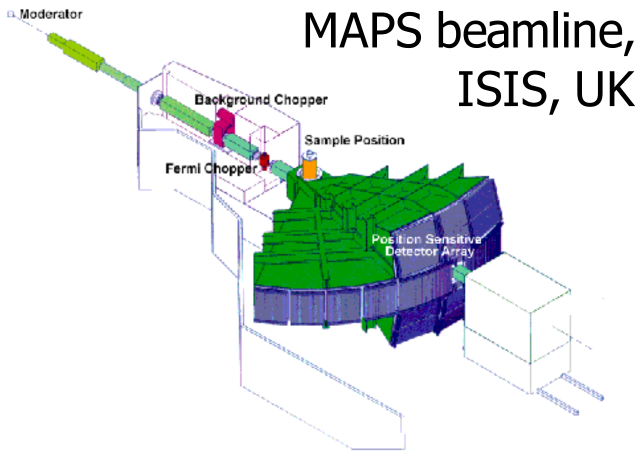




Magneto-Elastic Excitation in (Y,Lu)MnO_3

$$H = H_{spin} + H_{phonon} - \alpha' \sum_{\langle ij \rangle} \left(e_{O_{ij}i} \cdot u_i + e_{O_{ij}j} u_j \right) S_i \cdot S_j$$





MAPS beamline, ISIS, UK

Magneto-phonon mode

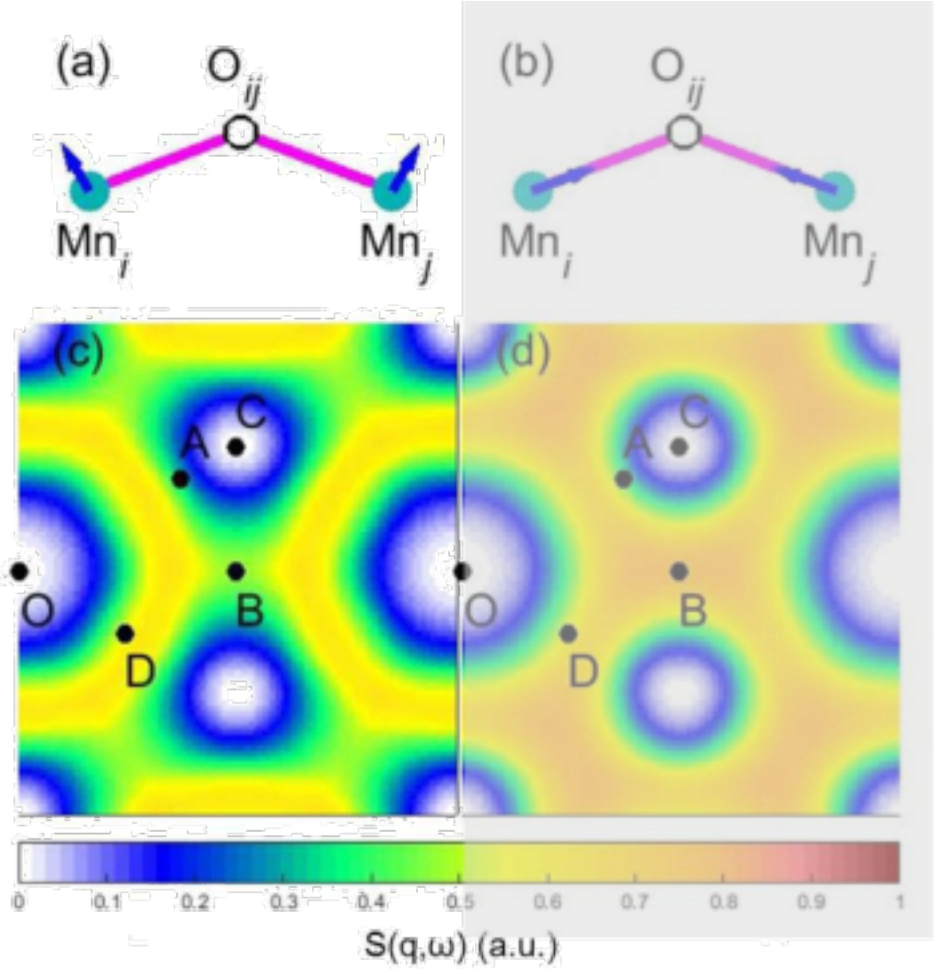
Joosung Oh

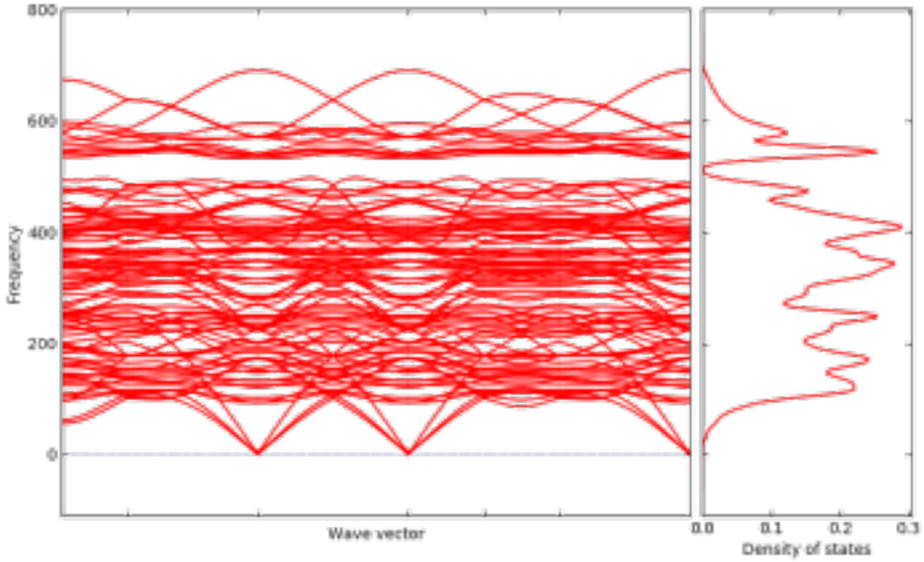
J. Oh, J-G. Park et al., Nat. Commun. **7**, 13146 (2016)

Exchange-Striction Model

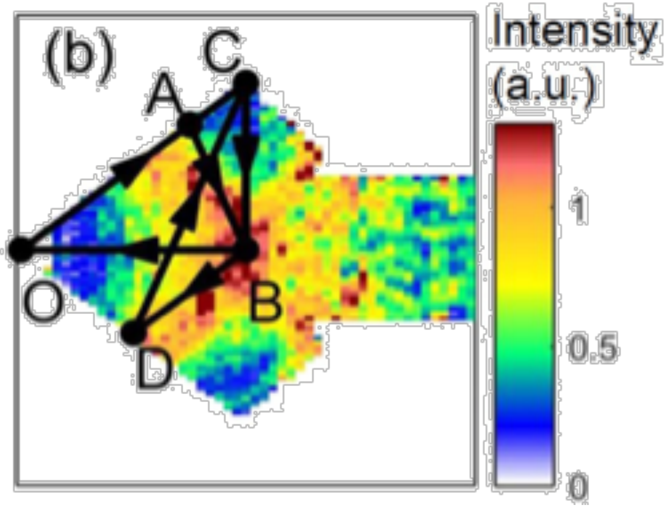
Mn-O Bond-length change is dominant for exchange-striction in $YMnO_3$

$$H = H_{spin} + \hbar \sum_{i=1}^{90} \omega_i b_k^\dagger b_k + \frac{\alpha J}{2d} \sum_{ij} \left(\boldsymbol{e}_{O_{ij}i} \cdot \boldsymbol{U}_i + \boldsymbol{e}_{O_{ij}j} \cdot \boldsymbol{U}_j \right) \boldsymbol{S}_i \cdot \boldsymbol{S}_j$$





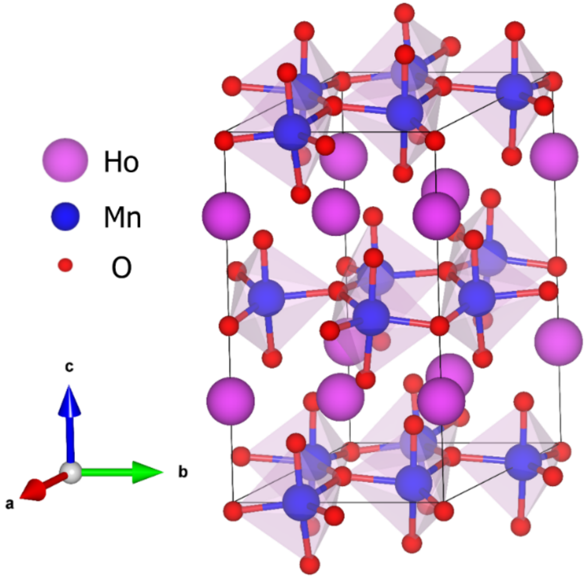
DFT phonon result of $YMnO_3$

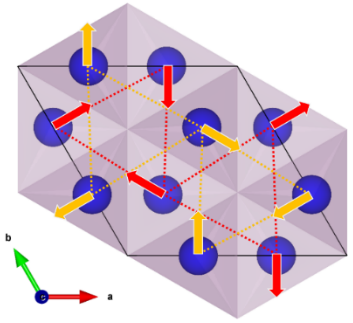


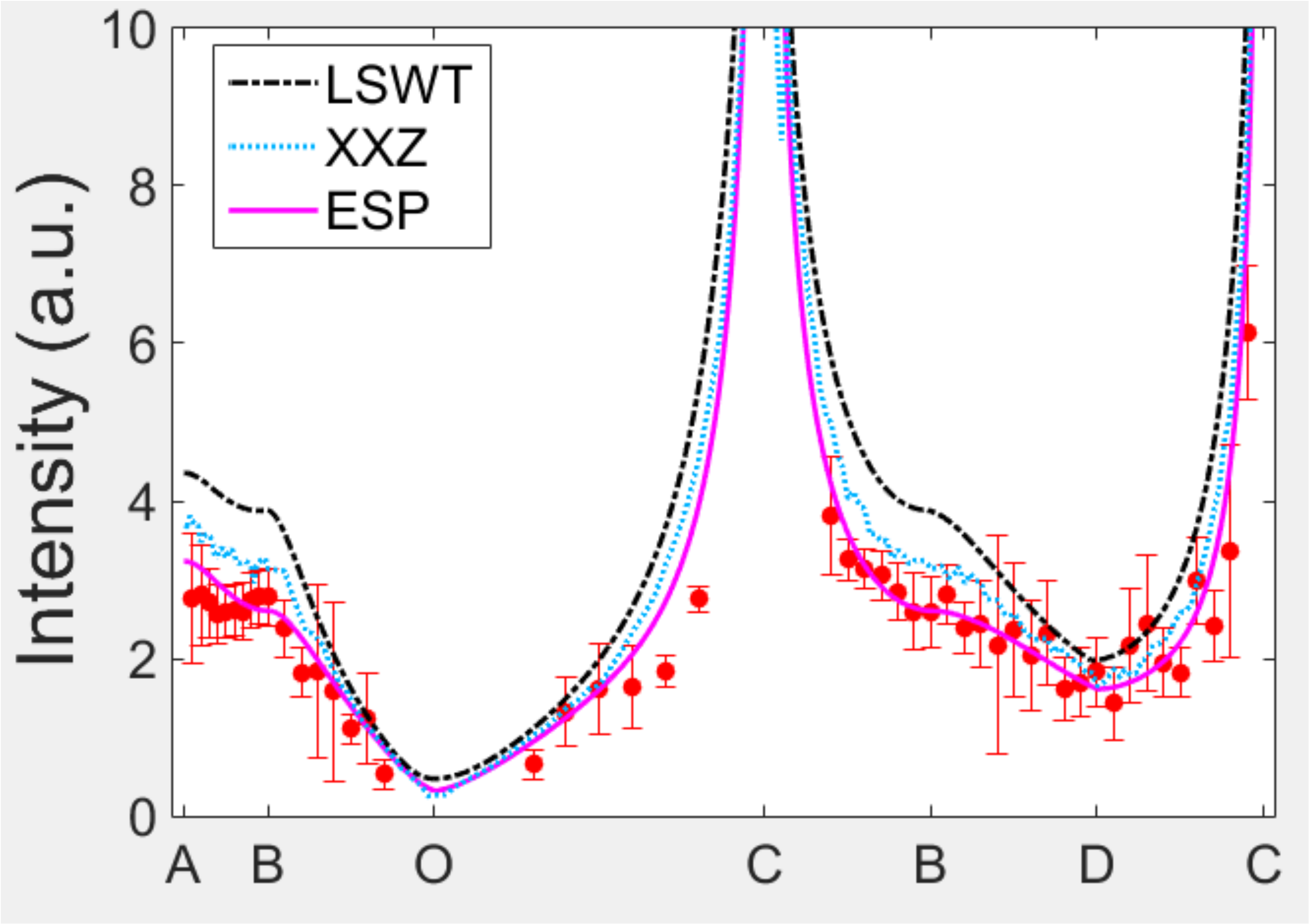
INS Dynamical Structure Factor

Dynamical Structure Factor: $HoMnO_3$

Taehun Kim, JGP et al., Phys. Rev. B 97, 201113(R) (2018)







Overall features are all similar for all three different models although the ESP model is slightly better.

Inelastic X-ray scattering (IXS) at Spring-8

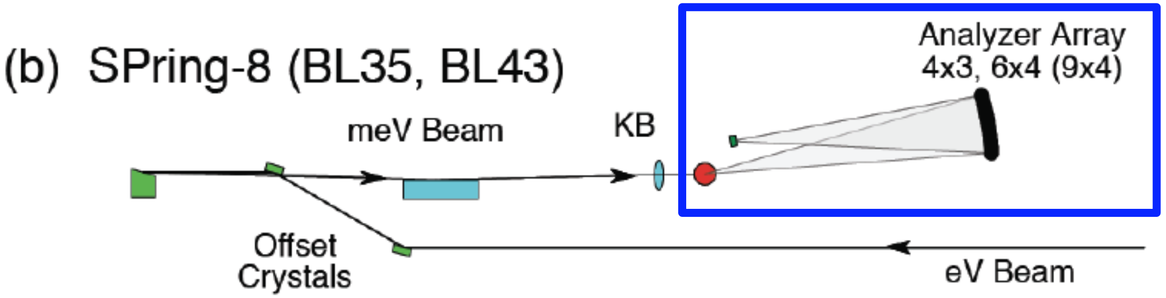
BL 43XU at Spring-8, Japan

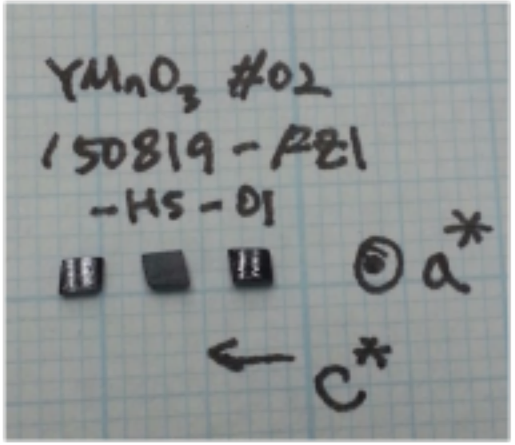
Kisoo Park

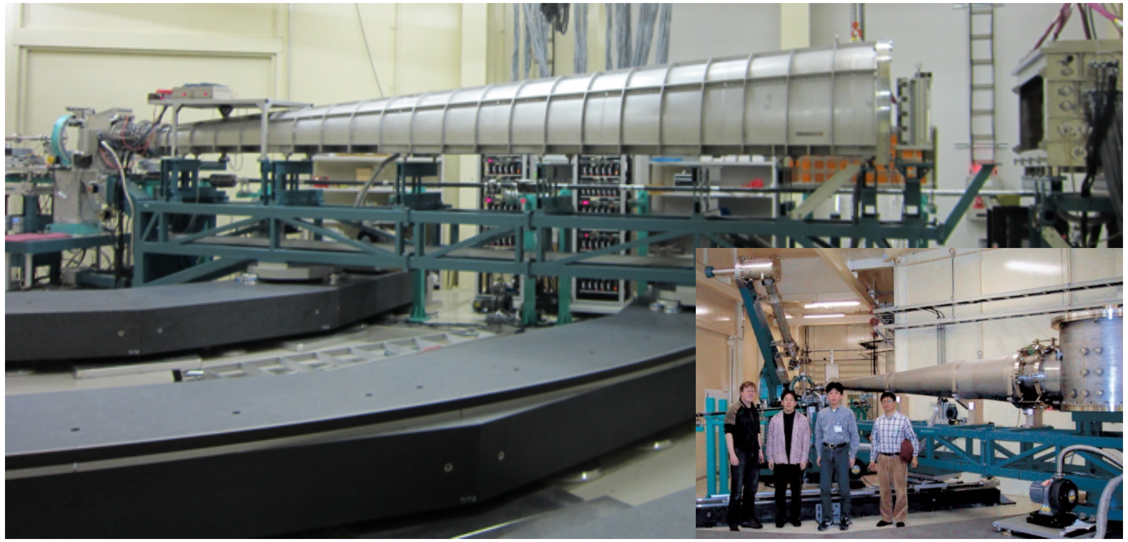
- Simultaneous measurement of 24 different q points
- q & E resolution: 0.05 Å^{-1} & 1.5 meV

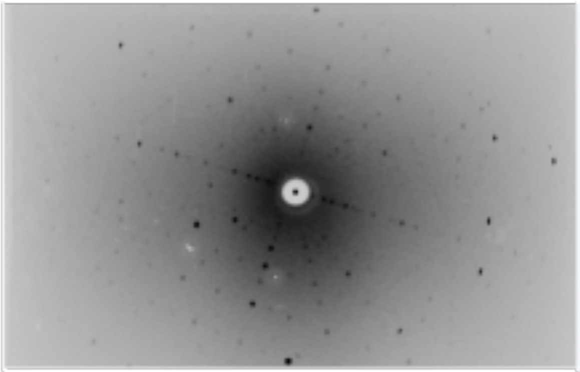
Main Operating Conditions at BL43LXU

Spectrometer	High Resolution (Atomic Dynamics)			
X-ray Energy (keV)	25.70	21.75	17.79	15.82
Energy Resolution FWHM (meV)	>0.75	>1.25	>2.8	~6
Analyzer Reflection Si (nnn)	(13 13 13)	(11 11 11)	(9 9 9)	(8 8 8)
Maximum Momentum Transfer (Å^{-1})	12	10	8.3	7.4
Photons at the Sample (Relative: 1 unit ~25 GHz)	~0.2	~1	~3	~10
Analyzer Solid Angle	~ 0.2 x 0.2 mrad^2 (Min.) to 9.4 x 8.9 mrad^2 (HxV, Max.)			
Beam Size at Sample Diameter, FWHM	~50 µm (Default), ~15 µm (Compound Focus)			



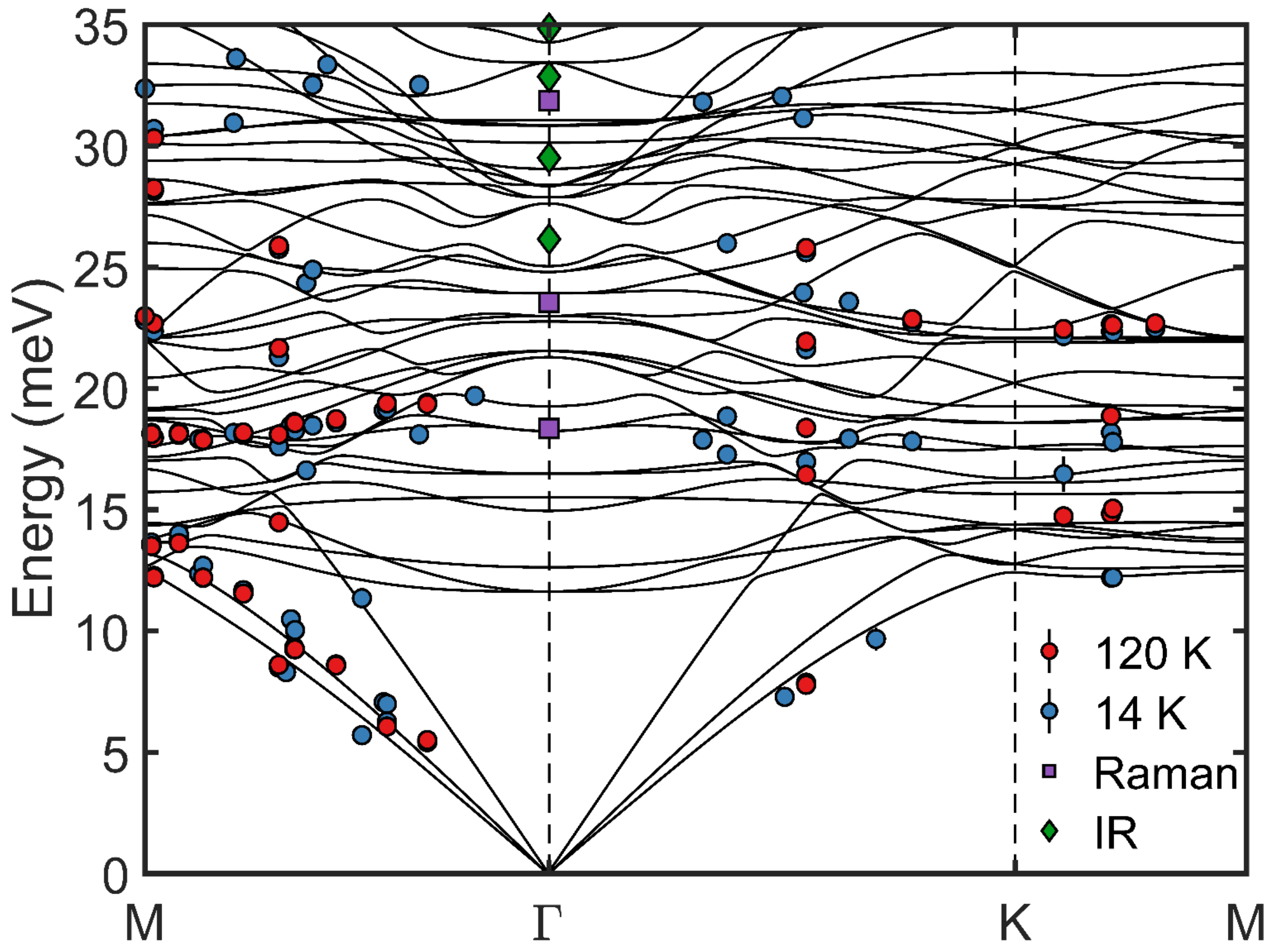






A. Q. R. Baron, arXiv: 1504.01098

IXS result and DFT calculations for $YMnO_3$

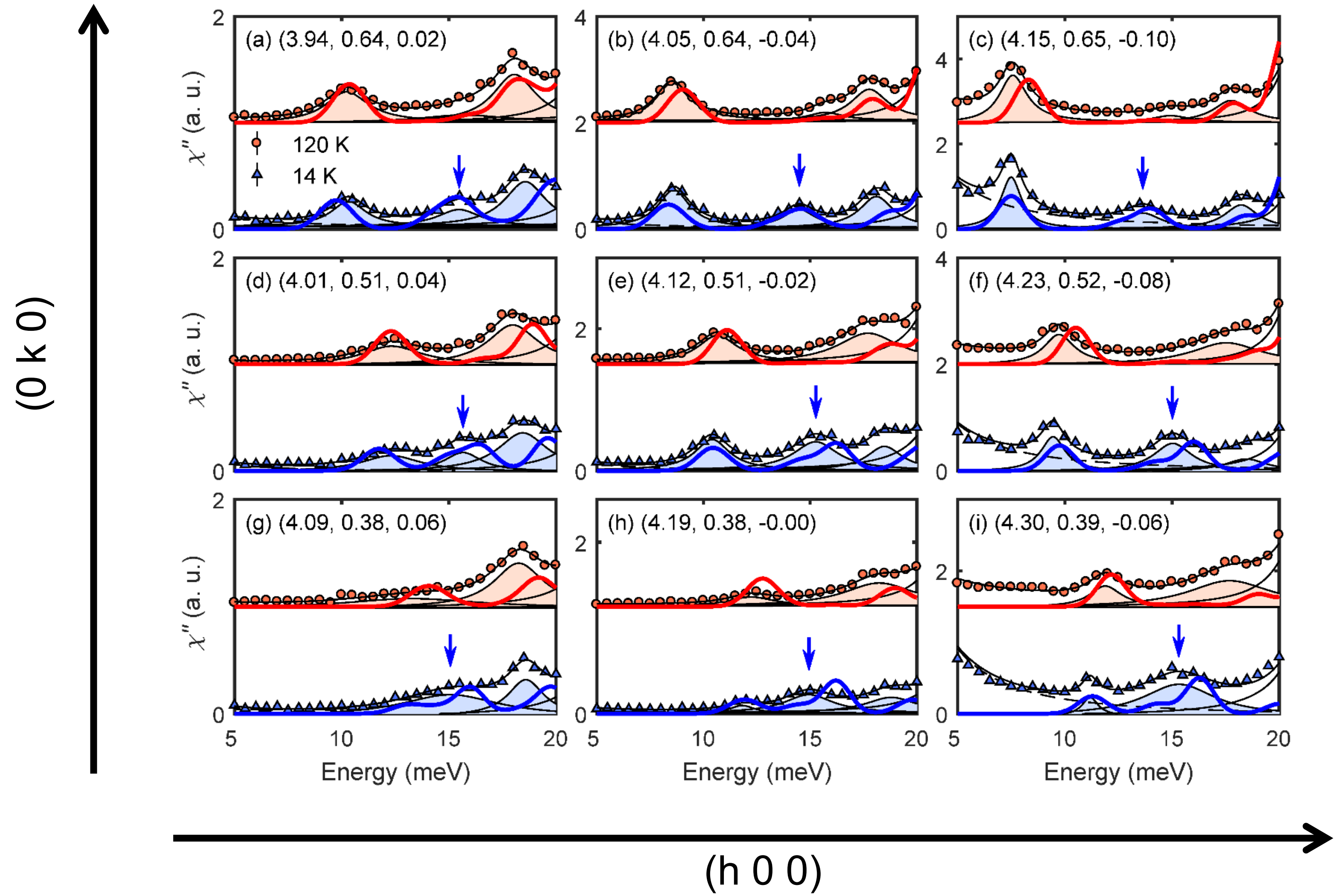


Key Observations

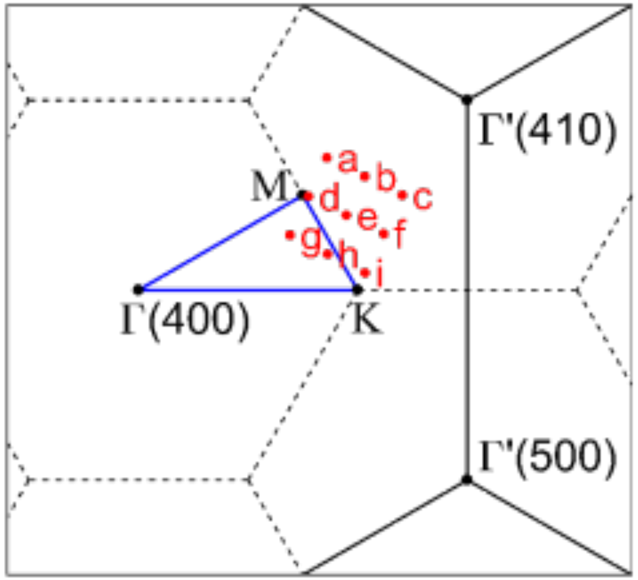
- We have succeeded in measuring several key phonons by using inelastic X-ray scattering technique.
- We have also found a significant shift induced by cooling.

Magneto-Elastic Excitations in $YMnO_3$

K. Park, J.-G. Park et al., in preparation



Kisoo Park

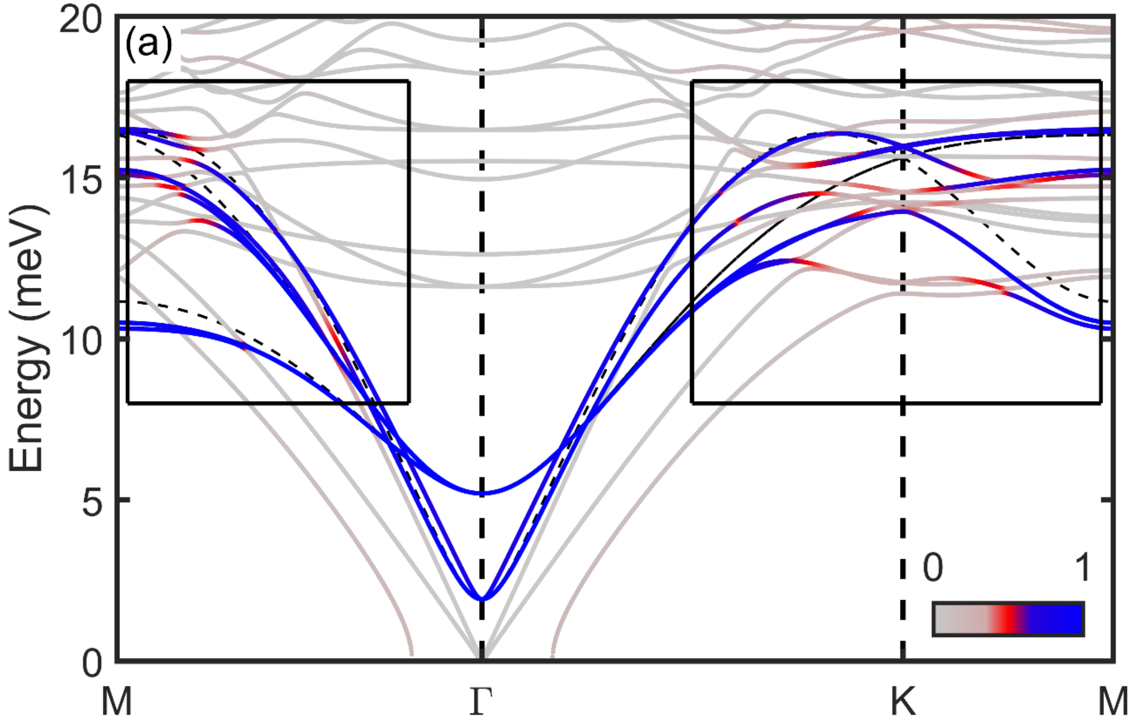


Red: HT (120 K)
Blue: LT (14 K)

How to quantify magnon-phonon hybridization?

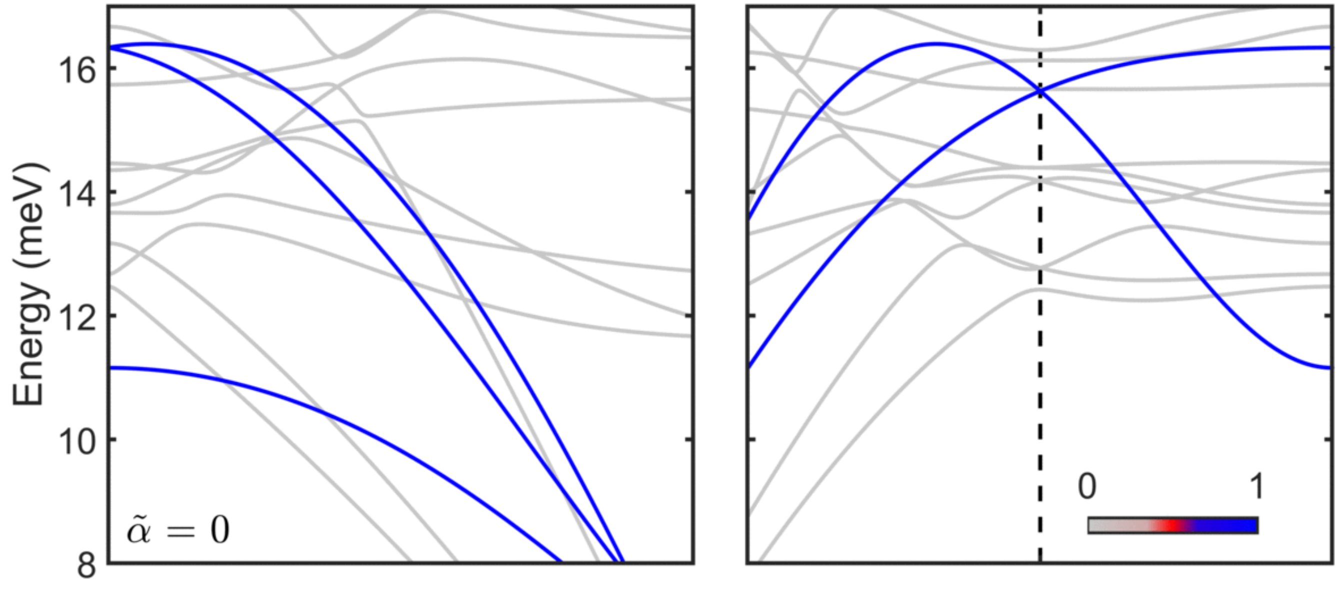
Each magneto-elastic modes can be characterized by the ratio between magnon/phonon components
$(p_i^{mag}(\boldsymbol{q}) + p_i^{ph}(\boldsymbol{q}) = 1,$ $p_i^{mag/ph}(\boldsymbol{q})$: magnon/phonon character of i−th band at **q** point).

Mangeto-elastic modes colored with the magnon character $p_i^{mag}(\boldsymbol{q})$



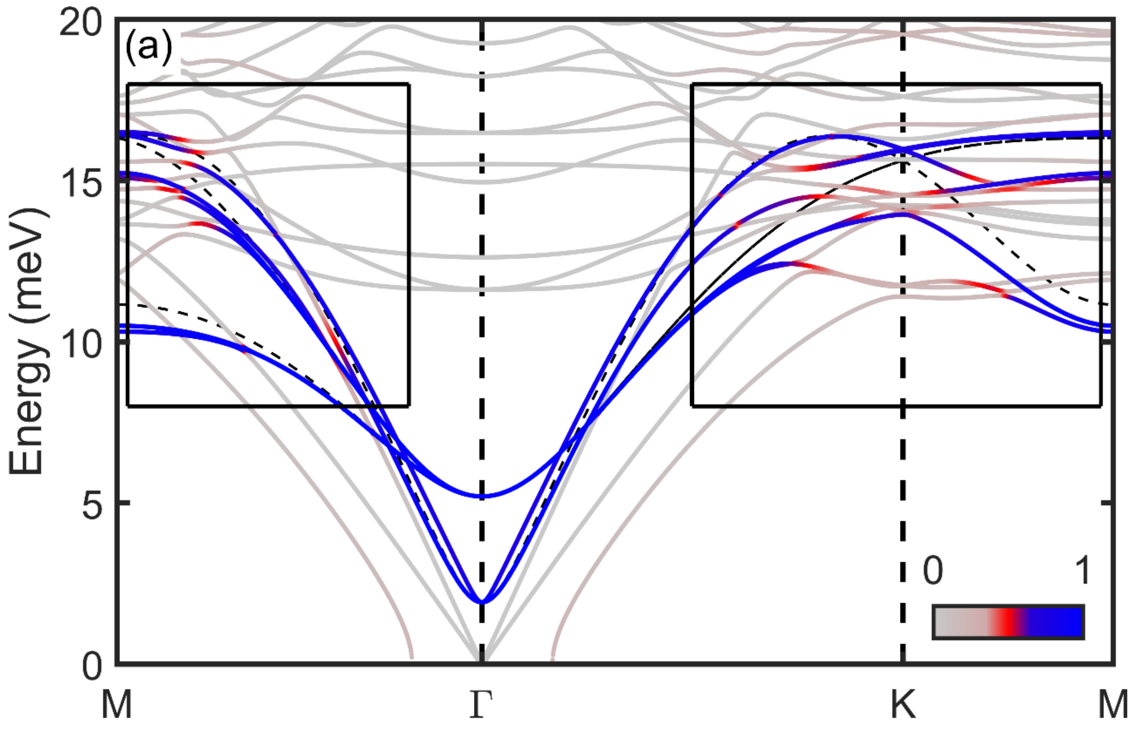
96×96 Matrix

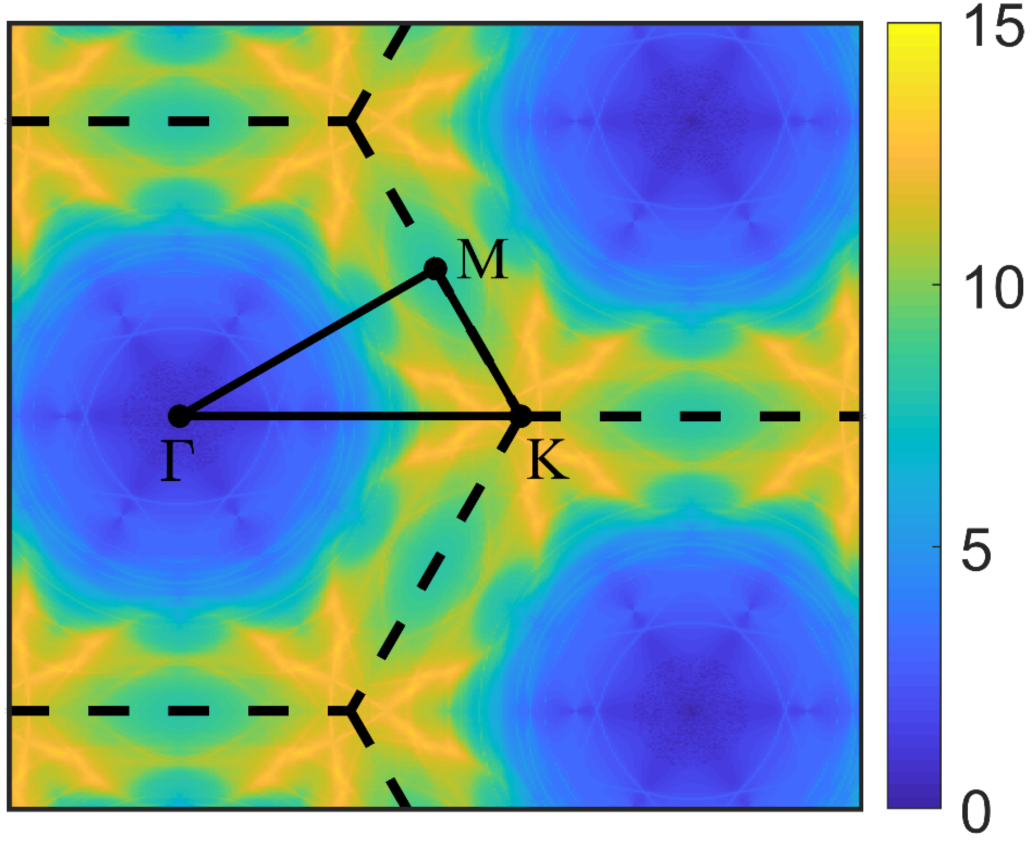
Matrix from: $H = S\sum_k X_{tot}^\dagger \begin{pmatrix} L & -iN^\dagger & M & -iN^\dagger \\ iN & \Omega & -iN & 0 \\ M & iN^\dagger & L & -iN^\dagger \\ iN & 0 & iN & \Omega \end{pmatrix} X_{tot}$



Magnon-Phonon Mixing Entropy

- Each magneto-elastic modes can be characterized by the ratio between magnon/phonon components ($p_i^{mag}(\boldsymbol{q}) + p_i^{ph}(\boldsymbol{q}) = 1,$ $p_i^{mag/ph}(\boldsymbol{q})$: magnon/phonon character of *i*−th band at **q** point).
- We can define the 'magnon-phonon mixing entropy' $S(\boldsymbol{q}) = -\sum_i p_i^{mag}(\boldsymbol{q}) log(p_i^{mag})(\boldsymbol{q})$ to quantify the mode-integrated momentum dependence of magnon-phonon coupling.





Detailed Phonon Mode Analysis

We can diagonalize pure magnon Hamiltonian in MP-coupled Hamiltonian.

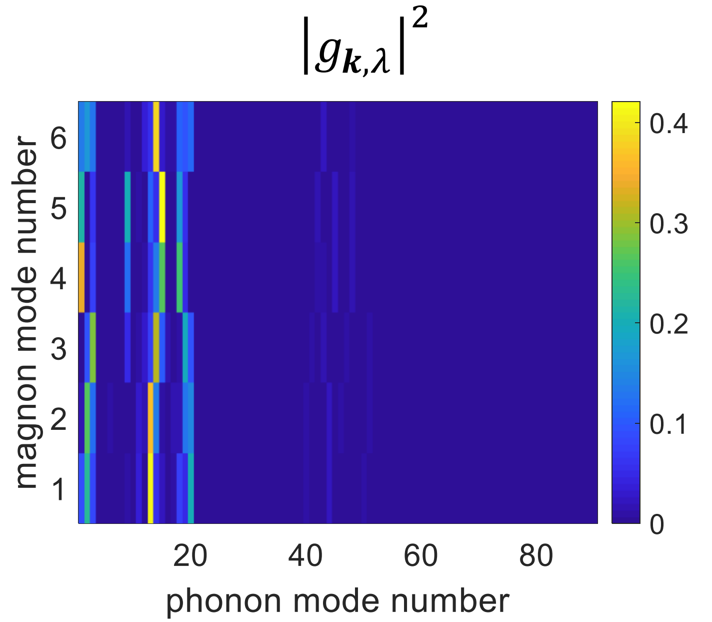
$$\mathcal{H}_{mag}(\boldsymbol{k}) = \begin{pmatrix} A_{\boldsymbol{k}} & B_{\boldsymbol{k}} \\ B_{\boldsymbol{k}} & A_{\boldsymbol{k}} \end{pmatrix}, \qquad \mathcal{H}_{mp}(\boldsymbol{k}) = \begin{pmatrix} A_{\boldsymbol{k}} & N^{\dagger}_{\boldsymbol{k},\lambda} & B_{\boldsymbol{k}} & N_{\boldsymbol{k},\lambda} \\ N_{\boldsymbol{k},\lambda} & E_{ph}(\boldsymbol{k},\lambda) & N^{\dagger}_{\boldsymbol{k},\lambda} & 0 \\ B_{\boldsymbol{k}} & N_{\boldsymbol{k},\lambda} & A_{\boldsymbol{k}} & N^{\dagger}_{\boldsymbol{k},\lambda} \\ N^{\dagger}_{\boldsymbol{k},\lambda} & 0 & N_{\boldsymbol{k},\lambda} & E_{ph}(\boldsymbol{k},\lambda) \end{pmatrix}$$

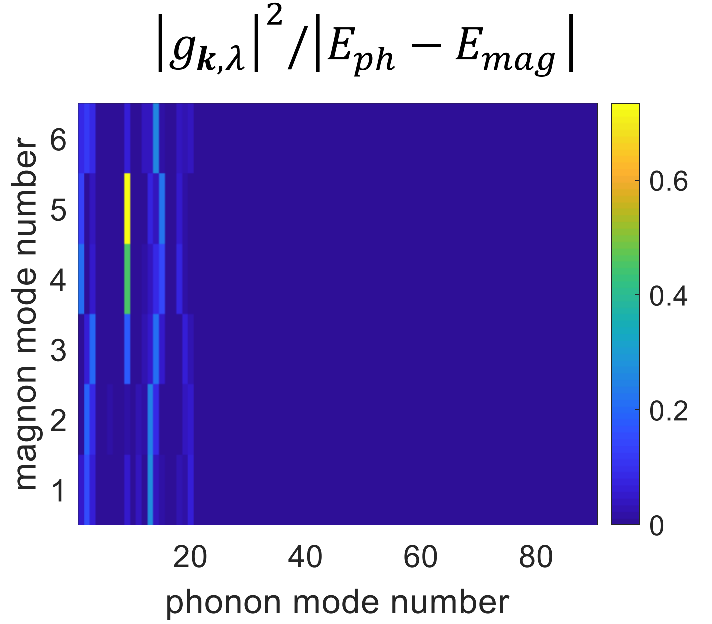
$$where\ V^{\dagger}_{mag} \cdot \mathcal{H}_{mag}(\boldsymbol{k}) \cdot V_{mag} = E_{mag}, V_{mag} = \begin{pmatrix} \alpha_{\boldsymbol{k}} & \beta_{\boldsymbol{k}} \\ \gamma_{\boldsymbol{k}} & \delta_{\boldsymbol{k}} \end{pmatrix}$$

$$\rightarrow \begin{pmatrix} \alpha_{\boldsymbol{k}} & 0 & \beta_{\boldsymbol{k}} & 0 \\ 0 & I & 0 & 0 \\ \gamma_{\boldsymbol{k}} & 0 & \delta_{\boldsymbol{k}} & 0 \\ 0 & 0 & 0 & I \end{pmatrix}^{\dagger} \cdot \begin{pmatrix} A_{\boldsymbol{k}} & N^{\dagger}_{\boldsymbol{k},\lambda} & B_{\boldsymbol{k}} & N_{\boldsymbol{k},\lambda} \\ N_{\boldsymbol{k},\lambda} & E_{ph}(\boldsymbol{k},\lambda) & N^{\dagger}_{\boldsymbol{k},\lambda} & 0 \\ B_{\boldsymbol{k}} & N_{\boldsymbol{k},\lambda} & A_{\boldsymbol{k}} & N^{\dagger}_{\boldsymbol{k},\lambda} \\ N^{\dagger}_{\boldsymbol{k},\lambda} & 0 & N_{\boldsymbol{k},\lambda} & E_{ph}(\boldsymbol{k},\lambda) \end{pmatrix} \cdot \begin{pmatrix} \alpha_{\boldsymbol{k}} & 0 & \beta_{\boldsymbol{k}} & 0 \\ 0 & I & 0 & 0 \\ \gamma_{\boldsymbol{k}} & 0 & \delta_{\boldsymbol{k}} & 0 \\ 0 & 0 & 0 & I \end{pmatrix}$$

$$= \begin{pmatrix} E_{mag}(\boldsymbol{k}) & g^{\dagger}_{\boldsymbol{k},\lambda} & 0 & g_{\boldsymbol{k},\lambda} \\ g_{\boldsymbol{k},\lambda} & E_{ph}(\boldsymbol{k},\lambda) & g^{\dagger}_{\boldsymbol{k},\lambda} & 0 \\ 0 & g_{\boldsymbol{k},\lambda} & E_{mag}(\boldsymbol{k}) & g^{\dagger}_{\boldsymbol{k},\lambda} \\ g^{\dagger}_{\boldsymbol{k},\lambda} & 0 & g_{\boldsymbol{k},\lambda} & E_{ph}(\boldsymbol{k},\lambda) \end{pmatrix}$$

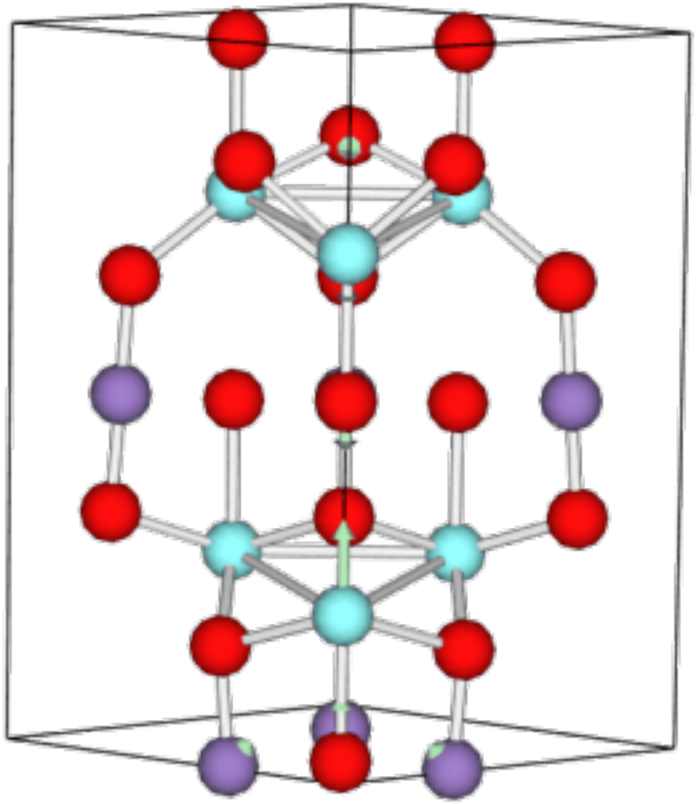
Mode-dependent magnon-phonon coupling strength

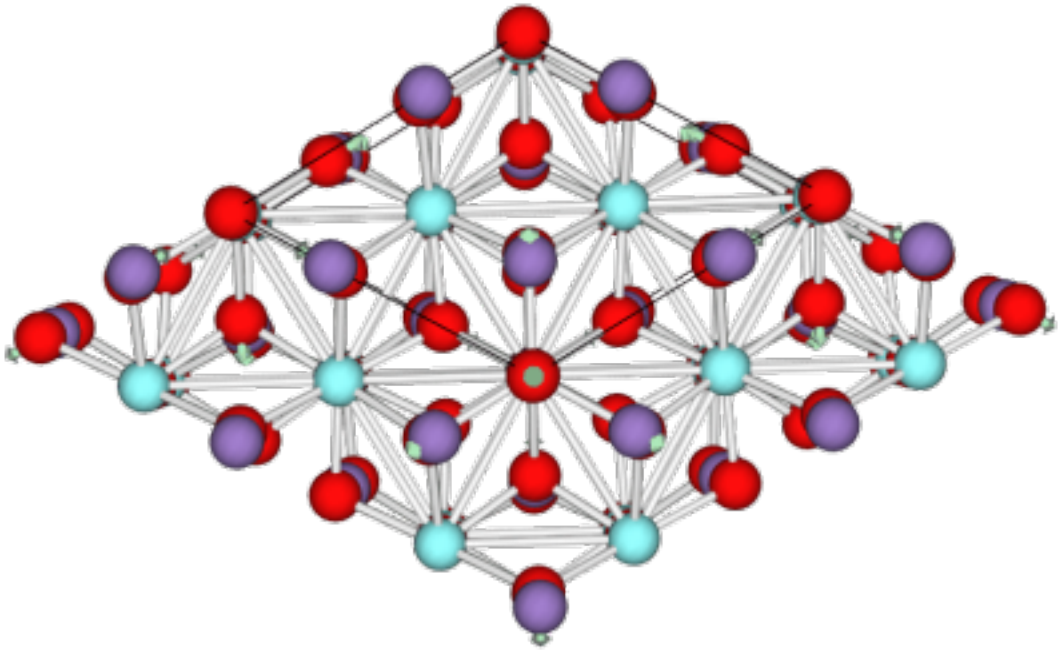




Mode Analysis via MP-coupled Hamiltonian

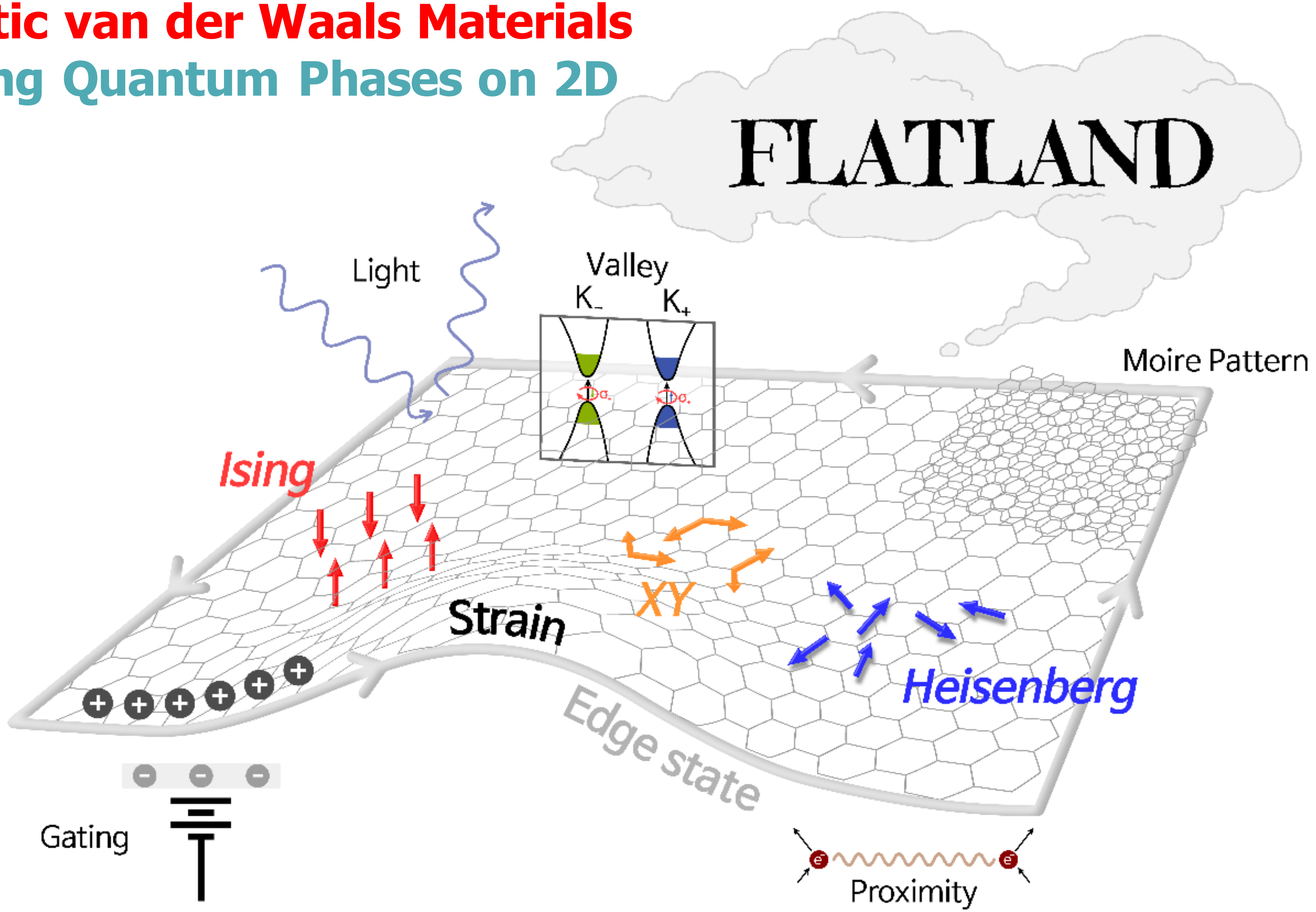
K point (1/3 1/3 0), 8^{th} phonon mode (16.17 meV)
→ Mn-trimer breathing phonon mode is most strongly coupled with the magnons at K point.





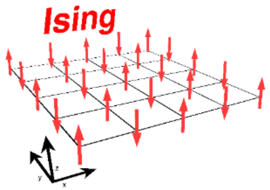
2D magnetic van der Waals Materials

Landscaping Quantum Phases on 2D

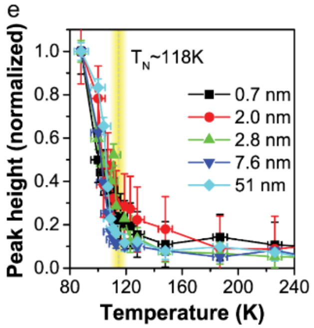


Je-Geun Park, J. Phys. Condens. Matter 28, 301001 (2016)
K. S. Burch, D. Mandrus & Je-Geun Park, Nature 563, 47 (2018)

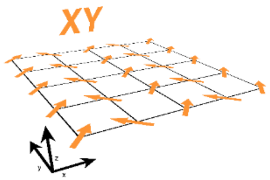
Magnetic Graphene & Model Magnetism



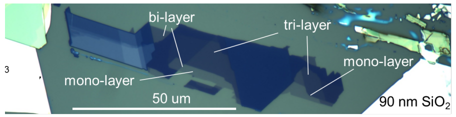
$FePS_3$



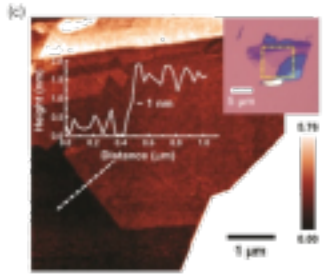
Jae-Ung Lee, JGP, Hyeonsik Cheong et al., Nano Lett. 16, 7433 (2016)

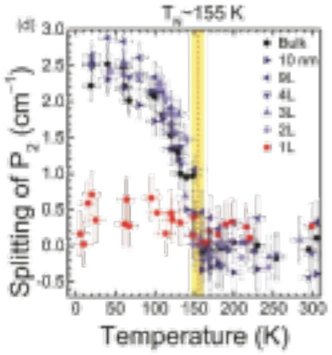


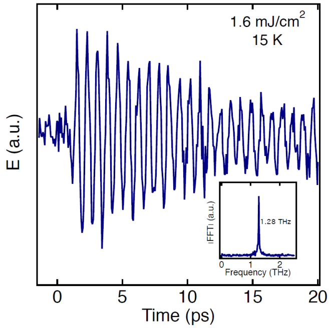
$NiPS_3$

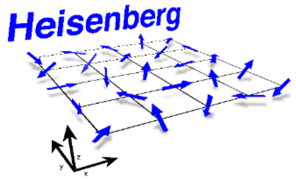


- S. Kim, JGP et al., Phys. Rev. Lett. 120, 136402 (2018)
- Kangwon Kim, JGP, Hyeonsik Cheong et al., Nat. Comm. 10, 345 (2019)
- Carina Belvin, JGP, Nuh Gedik, (in preparation)



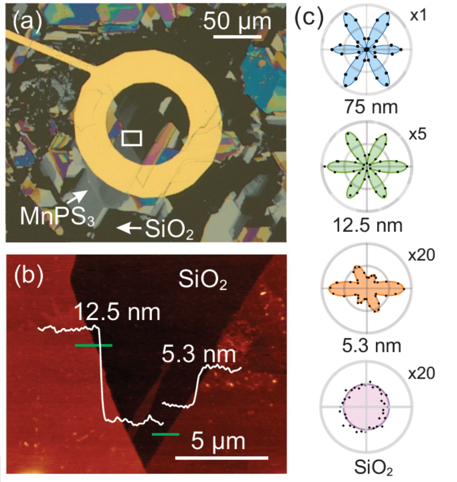


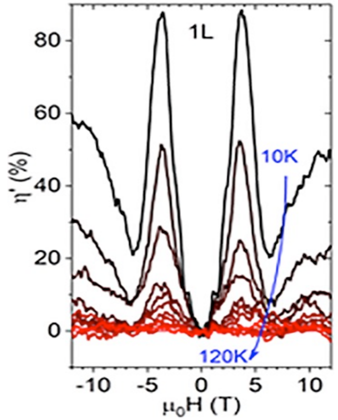




$MnPS_3$

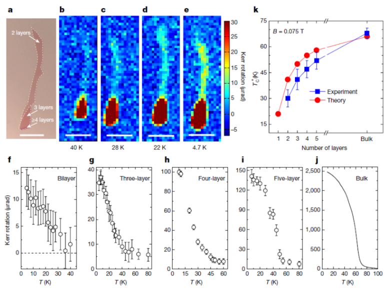
- K. Kim, JGP, Hyeonsik Cheong et al., 2D Materials (2019)
- H. Chu, JGP, D. Hsieh et al., PRL (submitted)





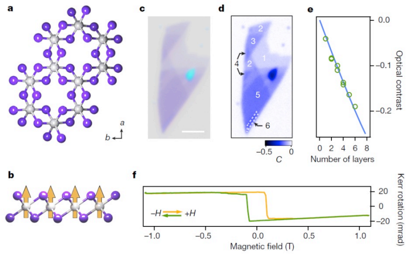
* Interesting Tunneling data from A. Morpurgo (submitted)

$CrGeTe_3$



C Gong et al., Nature, 546, 265 (2017)

CrI_3



B. Huang et al., Nature, 54 270 (2017)

Frustration on real 2D limits

Honeycomb Lattice

- Most of magnetic van der Waals materials have honeycomb lattice
- Ising: $FePS_3$, CrI_3, VI_3, $Fe_3Ge_2Te_6$ ...
- XY: $NiPS_3$
- Heisenberg: $MnPS_3$

cf: $RuCl_3$

Triangular Lattice

- 1T – TaS_2: possible quantum spin liquid state
  - M. Kratochvilova, NPG Quantum Materials 2, 42 (2017)
  - Y. J. Yu, Phys. Rev. B 96, 081111(R) (2017)

cf: Y Matsuda’s talk on Tuesday

Kagome Lattice

- $Pd_3P_2S_8$
- Nb_3I_8
- $Nb_3(Br,Cl)_8$

Acknowledgements

- Key Players at my group
  Kisoo Park, Joosung Oh, Ki Hoon Lee, Manh Duc Le, Jaehong Jeong, J. C. Leiner, Je-Geun Park (CCES, SNU)

- Sample preparations
  Hasung Sim (CCES, SNU)
  Hiroshi Eisaki & Yoshiyuki Yoshida (AIST, Japan)
  S. W. Cheong (Rutgers, USA)

- Neutron & x-ray experiments
  T. G. Perring & Hyungje Woo (ISIS, UK)
  Kenji Nakajima & Seiko Ohira-Kawamura (J-PARC, Japan)
  Zahra Yamani, W. J. L. Buyers (AECL, Canada)
  A. Q. R. Baron (Spring8, Japan)

- Theoretical supports
  Ho-Hyun Nahm, Ki Hoon Lee (CCES, SNU)
  A. L. Chernyshev (UCI, USA)

Je-Geun Park's Group

http://magnetism.snu.ac.kr

Jaehong Joeng

Taehun Kim

Kisoo Park

Kihoon Lee

Joosung Oh

- We have several positions open at the moment. If interested, please contact us.

Summary

- Strong magnon-phonon coupling produces a new hybrid magneto-elastic mode.
- We developed a quantitative formalism/procedure how to combine magnon and phonon.
- We provide a detailed momentum- and mode- analysis on the effect of magnon-phonon coupling.
- More general remark: In a noncollinear magnet, magnon mixes with other magnon and phonon, resulting in a creation of magneto-elastic excitation.