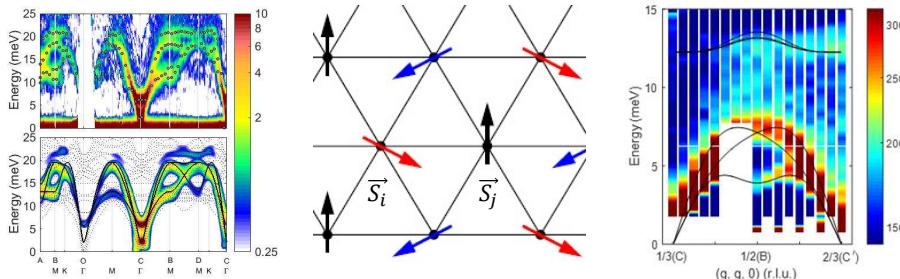


# Hybridization and Decay of Magnetic Excitations in Two-Dimensional Triangular Lattice Antiferromagnet



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J-PARC Symposium 2019, Tsukuba

26<sup>th</sup> September 2019

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## Outline

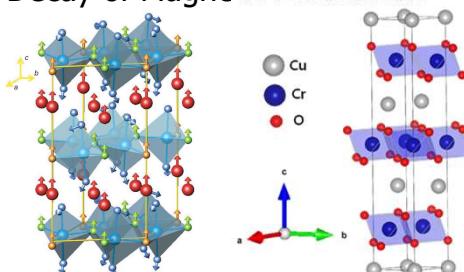
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- ◆ Magnon – Phonon/Magnon Interaction

- ◆ Hybridization and Decay of Magnetic Excitations

- RMnO<sub>3</sub>
- CuCrO<sub>2</sub>

- ◆ Summary



- S. Lee et al., Nature 451, 805 (2008)
- J. Oh et al., Phys. Rev. Lett. 111, 257202 (2013)
- J. Oh et al., Nature Communications 7, 13146 (2016)
- K. Park, et al., Phys. Rev. B 94, 104421 (2016)
- T. Kim et al., Phys. Rev. B 97, 201113(R) (2018)
- (Review) T. Kim et al., J. Phys. Soc. Jpn. 88, 081003 (2019)

**Interactions among Quasiparticles**

**Termination of quasiparticles in superfluid  $^4\text{He}$**

M. B. Stone et al., Nature **440**, 187 (2006)

The notion of a renormalized and stable quasiparticle is fundamental to modern theories of condensed matter physics.

**Strong interaction between triplon quasiparticles in  $\text{BiCu}_2\text{PO}_6$**

K. W. Plumb et al., Nature Physics **12**, 224 (2016)

Spontaneous Decay into multiparticle continuum state

Renormalization of single-triplon dispersion indicative of avoided level crossing

**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)

**Inelastic Neutron Scattering**

**Inelastic X-ray Scattering**

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

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

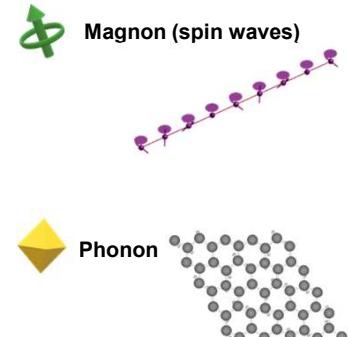
## Generic Hamiltonian

$$H_{tot} = H_{spin} + H_{pho} + H_{spin}^{pho}$$

$$H_{spin} = J \sum_{\langle ij \rangle} S_i \cdot S_j + D \sum_{\langle ij \rangle} S_i \times S_j + K \sum_i (S_i^n)^2$$

$$H_{pho} = \sum_{k,\lambda} \omega_{k,\lambda} \left( b_{k,\lambda}^\dagger b_{k,\lambda} + \frac{1}{2} \right)$$

$H_{spin}^{pho}$  = Mixing terms of magnons and phonons

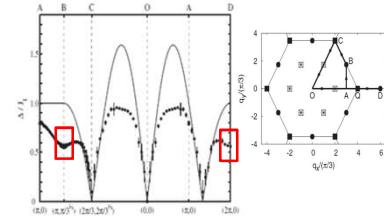


## Magnon-Magnon Interaction

cf. Talk by H Tanaka on Wednesday

- **Roton-like minimum:** W. Zheng et al., PRL (06)

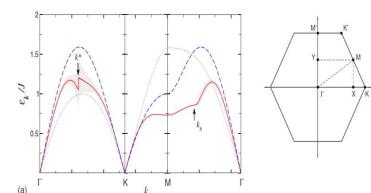
Quantum Monte Carlo Study  
*W. Zheng et al., PRL 96, 057201 (2006)*



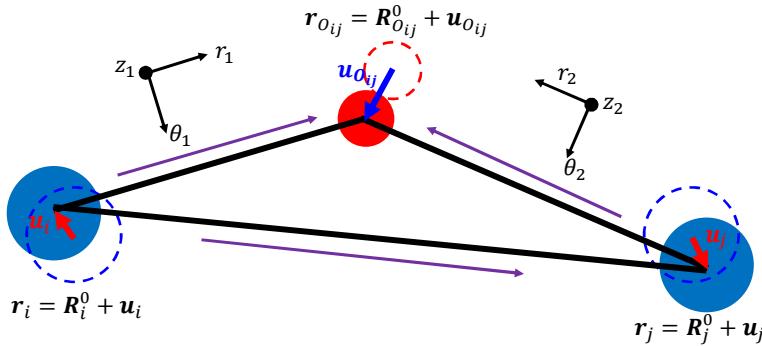
- **Magnon decay & Flat mode :** M. E. Zhitomirsky and A. L. Chernyshev, PRL (06); O. A. Starykh, A. Chubukov, & A. G. Abanov, PRB (06)

Nonlinear Spin Wave Theory  
*A. L. Chernyshev et al., PRB 79, 144416 (2009)*

- See also a recent review: M. E. Zhitomirsky, & A. L. Chernyshev, Rev. Mod. Phys. **85**, 219–242 (2013)



## Magnon-Phonon coupling via exchange-striction



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

$$J_{ij} (\mathbf{R}_i, \mathbf{R}_j, \mathbf{R}_{ij}) = J_0 + (\mathbf{u}_1 \cdot \nabla_1 + \mathbf{u}_2 \cdot \nabla_2 + \mathbf{u}_3 \cdot \nabla_3) J_{ij} + \dots$$

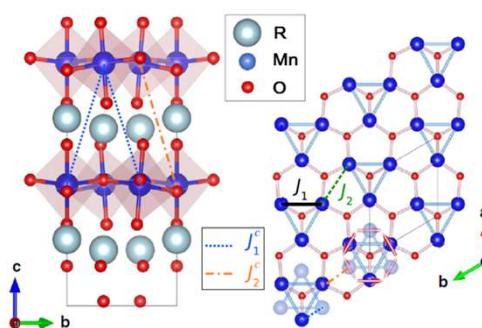
$$(\mathbf{u}_1 \cdot \nabla_1 + \mathbf{u}_2 \cdot \nabla_2 + \mathbf{u}_3 \cdot \nabla_3) J_{ij} = (\mathbf{u}_{0ij} - \mathbf{u}_i) \cdot \nabla_1 (J_{ij}) + (\mathbf{u}_{0ij} - \mathbf{u}_j) \cdot \nabla_2 (J_{ij}) + (\mathbf{u}_j - \mathbf{u}_i) \cdot \nabla_3 (J_{ij})$$

Superexchange-striction      Direct exchange-striction

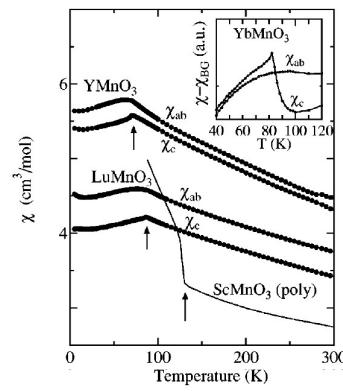
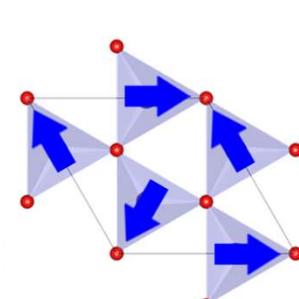
## 2D Triangular Antiferromagnet RMnO<sub>3</sub>

- Mn atoms form triangular layers
- 120° order due to geometrical frustration
- YMnO<sub>3</sub>: T<sub>N</sub>=75 K, θ<sub>CW</sub>=705 K
- LuMnO<sub>3</sub>: T<sub>N</sub>=90 K, θ<sub>CW</sub>=887 K

Crystal structure



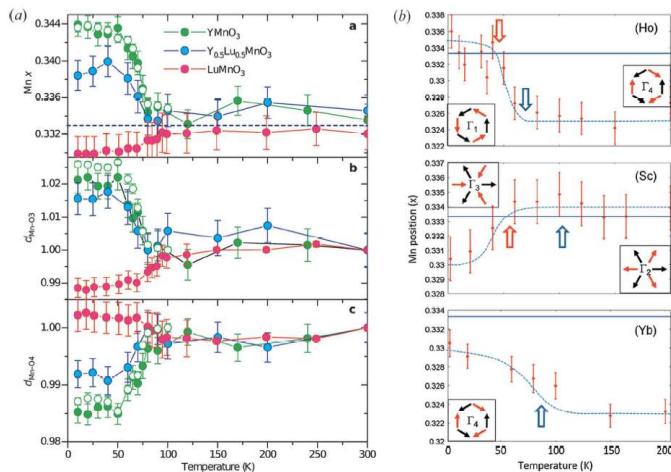
Magnetic structure



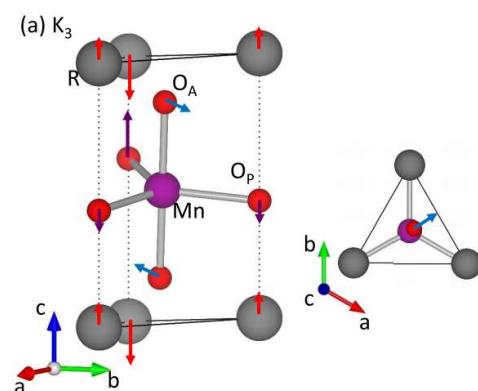
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## Mn-Trimerization and Ferroelectricity

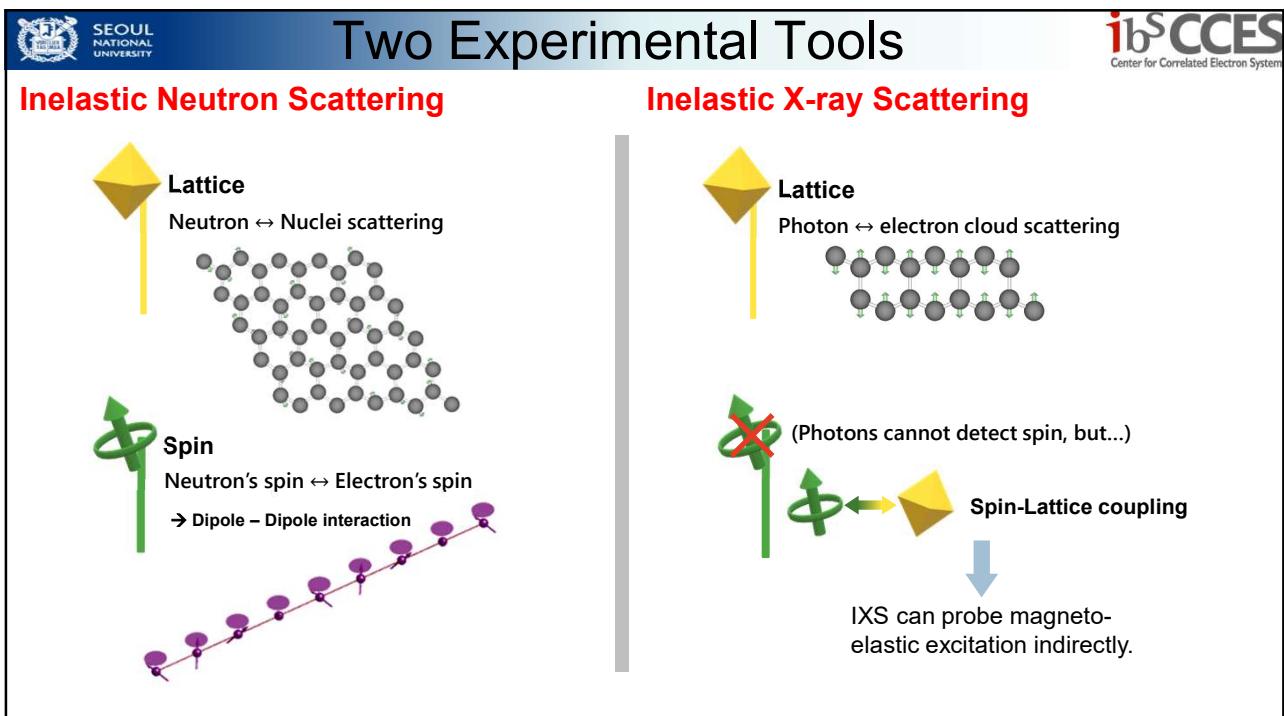
**ibS CCES**  
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S. Lee, J.-G. Park et al, Nature **451**, 805 (2008)X. Fabreges et al, PRL **103**, 067204 (2009)H. Sim, J.-G. Park et al, JPCM **30**, 105601 (2018)

Strong spin-lattice coupling



Ferroelectricity

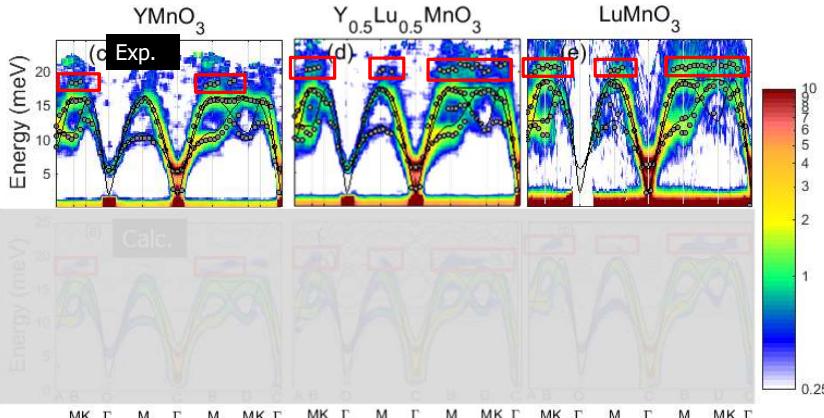




## Magneto-Elastic Excitation in h-(Y,Lu)MnO<sub>3</sub>

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$$H = H_{spin} + H_{phonon} - \alpha' \sum_{\langle ij \rangle} (\mathbf{e}_{O_{ij}i} \cdot \mathbf{u}_i + \mathbf{e}_{O_{ij}j} \cdot \mathbf{u}_j) \mathbf{S}_i \cdot \mathbf{S}_j$$



MAPS beamline,  
ISIS, UK

Magneto-  
phonon mode

Joosung Oh



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

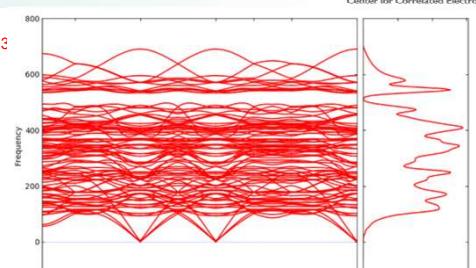
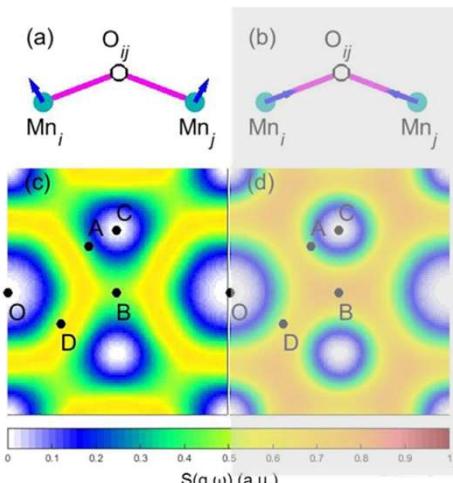


## Exchange-Striction Model

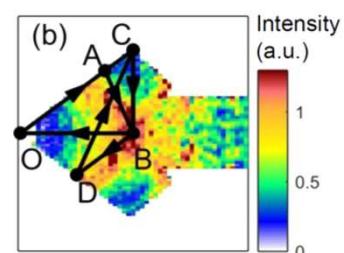
**iB<sup>S</sup>CCES**  
Center for Correlated Electron System

Mn-O Bond-length change is dominant for exchange-striction in YMnO<sub>3</sub>

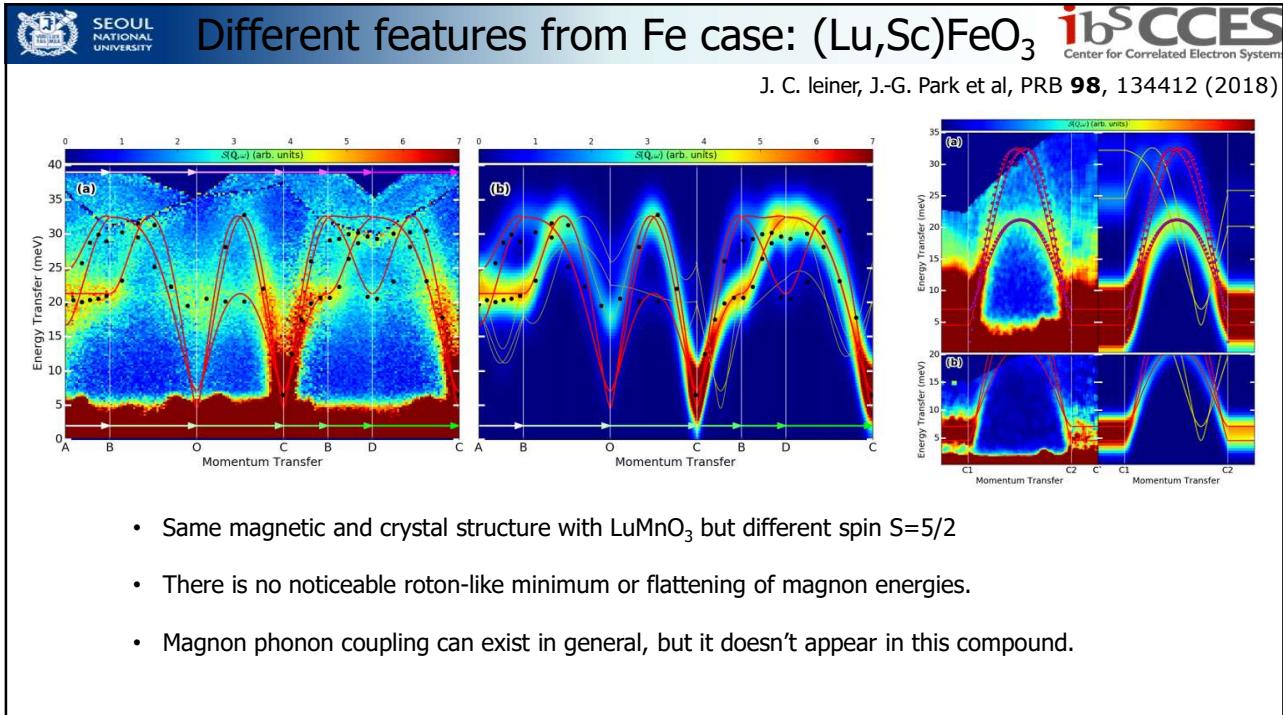
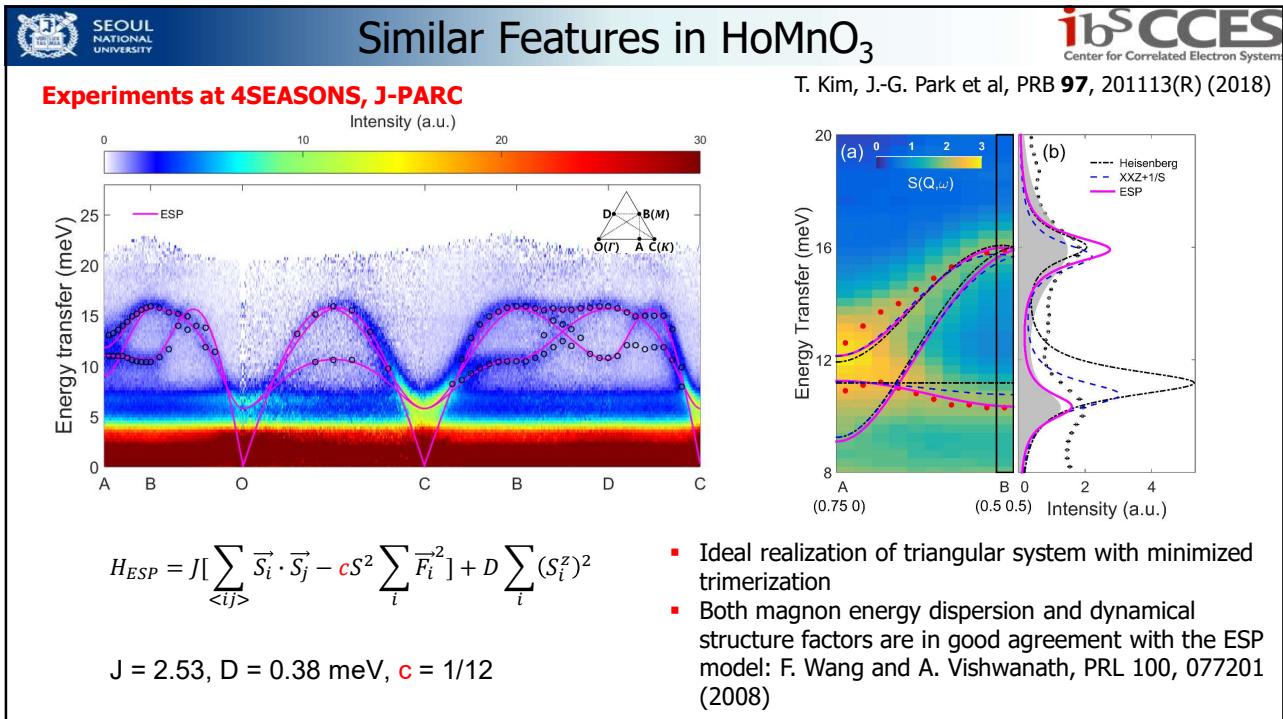
$$H = H_{spin} + \hbar \sum_{i=1}^{90} \omega_i b_k^\dagger b_k + \frac{\alpha J}{2d} \sum_{ij} (\mathbf{e}_{O_{ij}i} \cdot \mathbf{u}_i + \mathbf{e}_{O_{ij}j} \cdot \mathbf{u}_j) \mathbf{S}_i \cdot \mathbf{S}_j$$



DFT phonon result of YMnO<sub>3</sub>

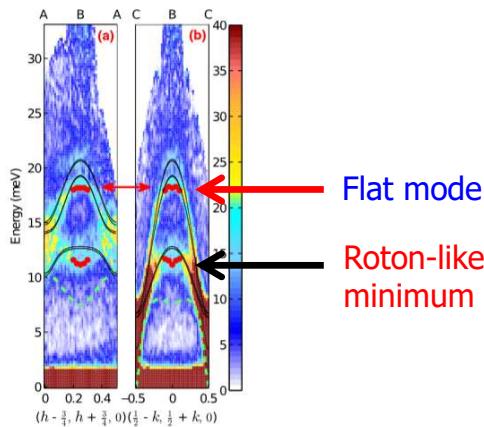
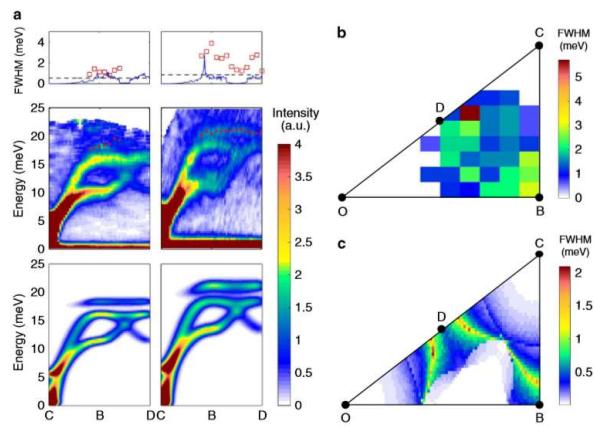


INS Dynamical Structure Factor



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## Decay of Magnon and Magneto-Elastic Excitations

J. Oh, J.-G. Park et al, PRL **111**, 257202 (2013)J. Oh, J.-G. Park et al, Nat. Commun. **7**, 13146 (2016)

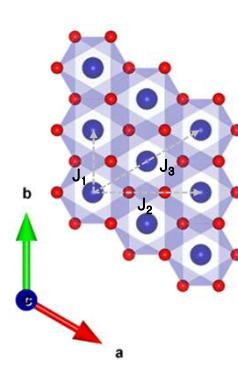
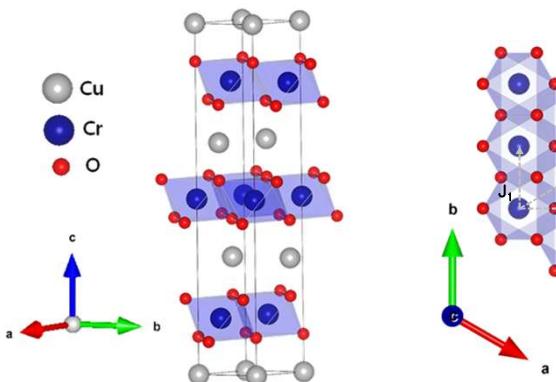
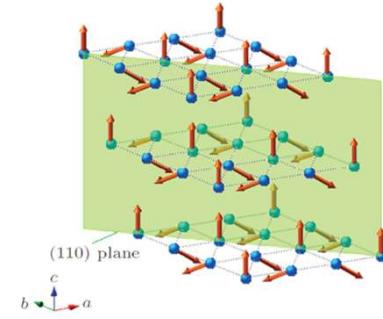
Key features of magnon / magneto-elastic excitations decay

- (1) The roton-like minimum at B point
- (2) Flat dispersion of the higher energy mode at same point
- (3) Intrinsic linewidth broadening of magneto-elastic mode

cf. Talk by H Tanaka on Wednesday

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- $a = b = 2.9747 \text{ \AA}$ ,  $c = 17.1015 \text{ \AA}$  ( $\bar{R}\bar{3}m$ )
- Proper helix magnetic structure with  $\mathbf{k} = (0.329 \ 0.329 \ 0)$  → Nearly classical  $120^\circ$  ordering
- Cr<sup>3+</sup> (3d<sup>3</sup>) at octahedral site. → 3 t<sub>2g</sub> quenched orbitals with  $S = 3/2$ .  
→ Isotropic exchange interaction with Heisenberg spin

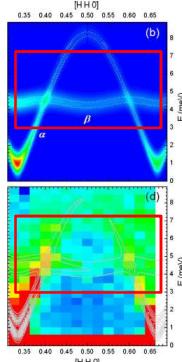
Magnetic structure of CuCrO<sub>2</sub>



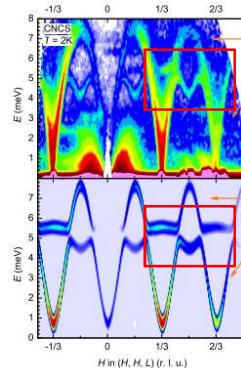
## Three Spin Waves Measurements of CuCrO<sub>2</sub>



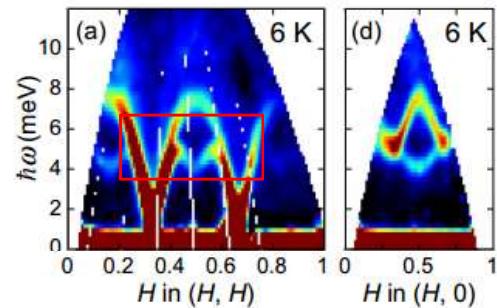
M. Poiñar *et al.*, PRB **81**, 104411 (2010)



M. Frontzek *et al.*, PRB **84**, 094448 (2011)



R. Kajimoto *et al.*, JPSJ **84**, 074708 (2015)



## Magnon-Phonon Coupled Model in CuCrO<sub>2</sub>

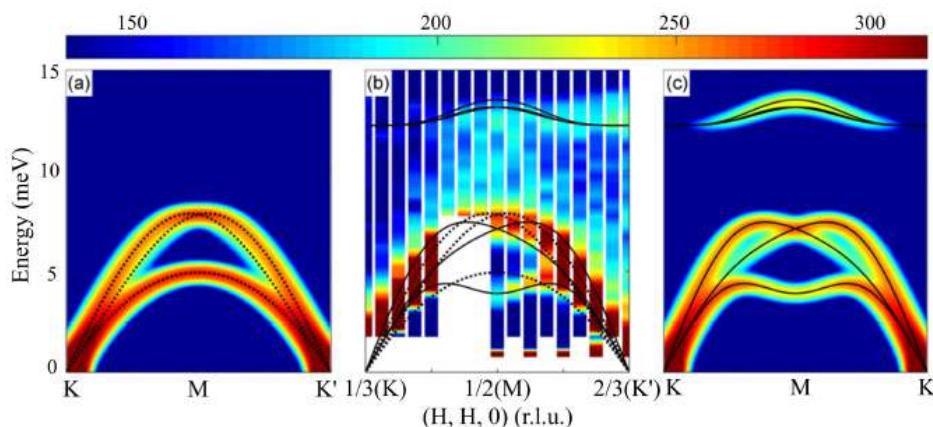


- $J_1 = -1.57 \text{ meV}$ ,  $J_2 = 0.045 \text{ meV}$ ,  $J_3 = -0.145 \text{ meV}$   
 $c = 16.8 \text{ meV/Å}$

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

**Experiments at TAIPAN, ANSTO**

$$J_{ij} = J(|\vec{u}_i - \vec{u}_j|) \cong J[1 - c \hat{e}_{ij} \cdot (\vec{u}_i - \vec{u}_j)]$$





# Acknowledgements



## Key Players at my group

Kisoo Park, Joosung Oh, Taehoon Kim, Pyeongjae Park,  
Manh Duc Le, Jaehong Jeong, J. C. Leiner, Je-Geun Park (CCES, SNU)



## Sample Preparation

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



## Neutron & X-ray Experiment

T. G. Perring, Hyungje Woo (ISIS, UK)  
Kazuki Iida, Kazuya Kamazawa, Kenji Nakajima, Seiko Ohira-Kawamura (J-PARC, Japan)  
Kirrily C. Rule (ANSTO, Australia)  
Zahra Yamani (AECL, Canada)  
A. Q. R. Baron (Spring8, Japan)



## Theoretical Support

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



# Je-Geun Park's Group



<http://magnetism.snu.ac.kr>



Taehoon Kim

Kisoo Park

Je-Geun Park's Group

Pyeongjae Park

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.

