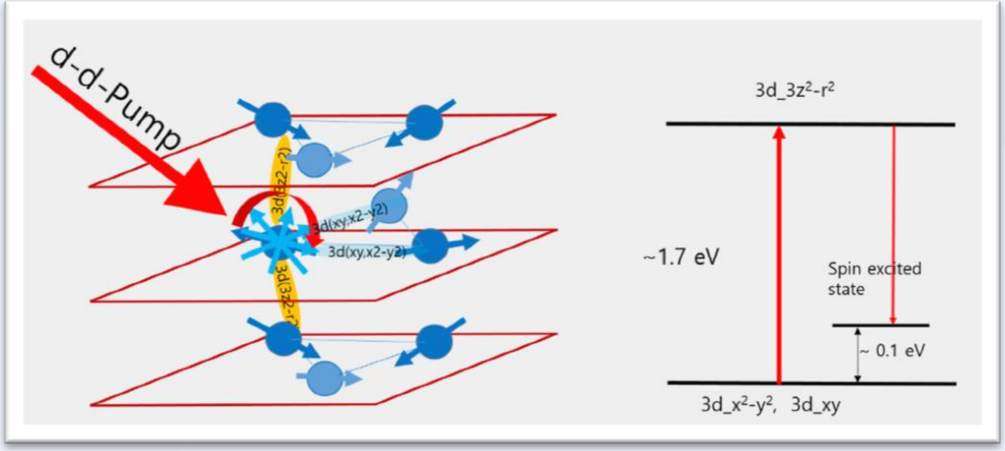
Raman study of spin excitations in hexagonal $RMnO_3$

October 16, 2019
고려대학교 물리학과



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Education
1988.8 PhD, University of Illinois at Urbana-Champaign (A.C. Anderson)
1986.5 MS, University of Illinois at Urbana-Champaign (A.C. Anderson)
1983.2 BS, Seoul National University, Department of Physics
PhD Thesis:
Phonon-dislocation interaction in LiF and KCl crystals

Professional Experience:
2000. 3 - present : Professor, Department of Physics and Division of nano-sciences, Ewha Womans University
2009.3 – 2010. 2 : Director, Basic Science Research Institute, Ewha Womans University
2005. 5 - 2008. 4 : Editor, Journal of the Korean Physical Society.
2002. 3 – 2004. 2: Chief Secretary, Condensed Matter Division, Korean Physical Society.
1998. 8 – 2002. 2 : Visiting Research Associate Professor, Physics, University of Illinois at Urbana-Champaign
1994.9 - 1999.8: Associate Professor, Department of Physics, Ewha Womans University
1990.9 - 1994.8 : Assistant Professor, Department of Physics, Ewha Womans University
1988.9 - 1990.8 : IBM Thomas J. Watson Research Center, Post-Doctor

Awards:
Korean Government Fellowship for Studying Abroad, 1983
Award for Prospective Young Scientists, Korean Physical Society, 1996
Ewha Best Lecturer Award, 2006

CONTRIBUTORS

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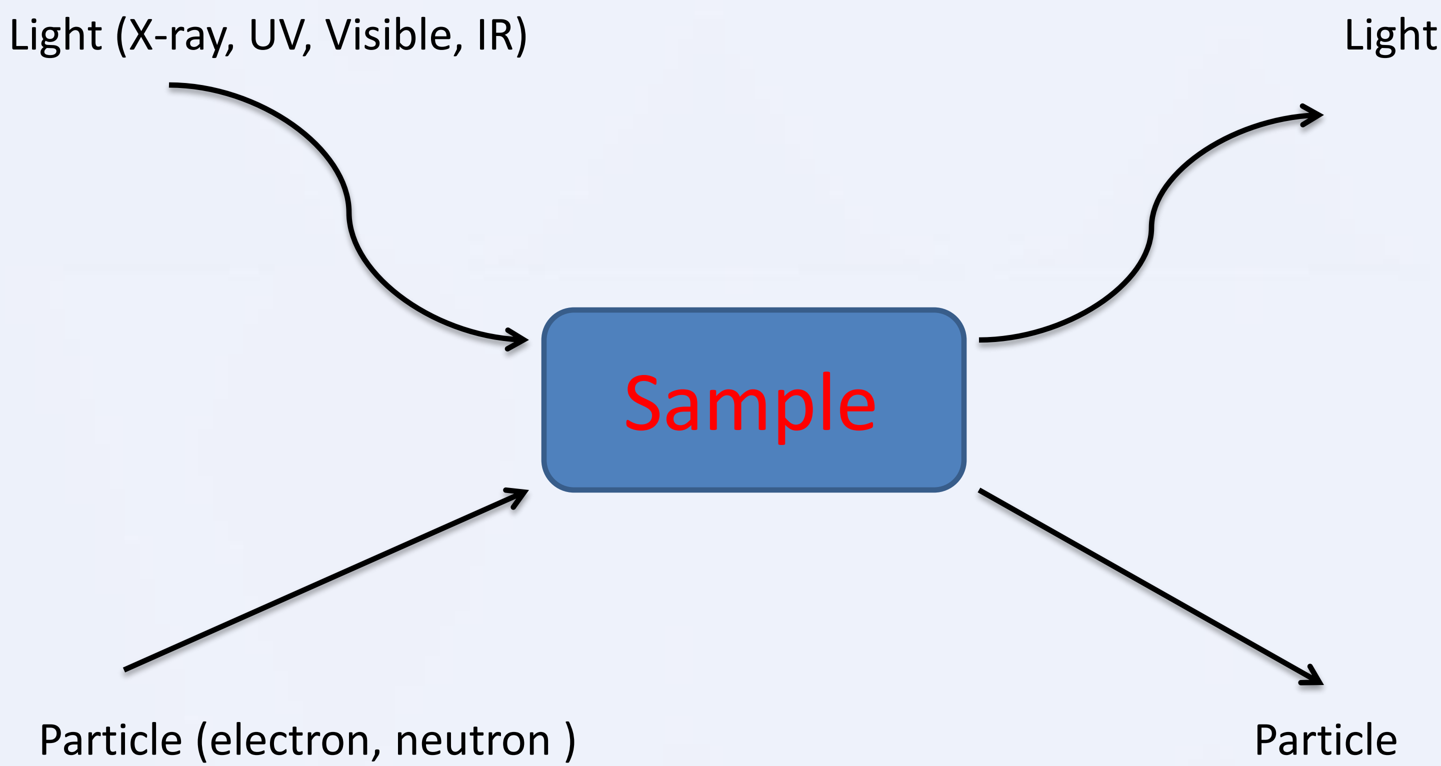
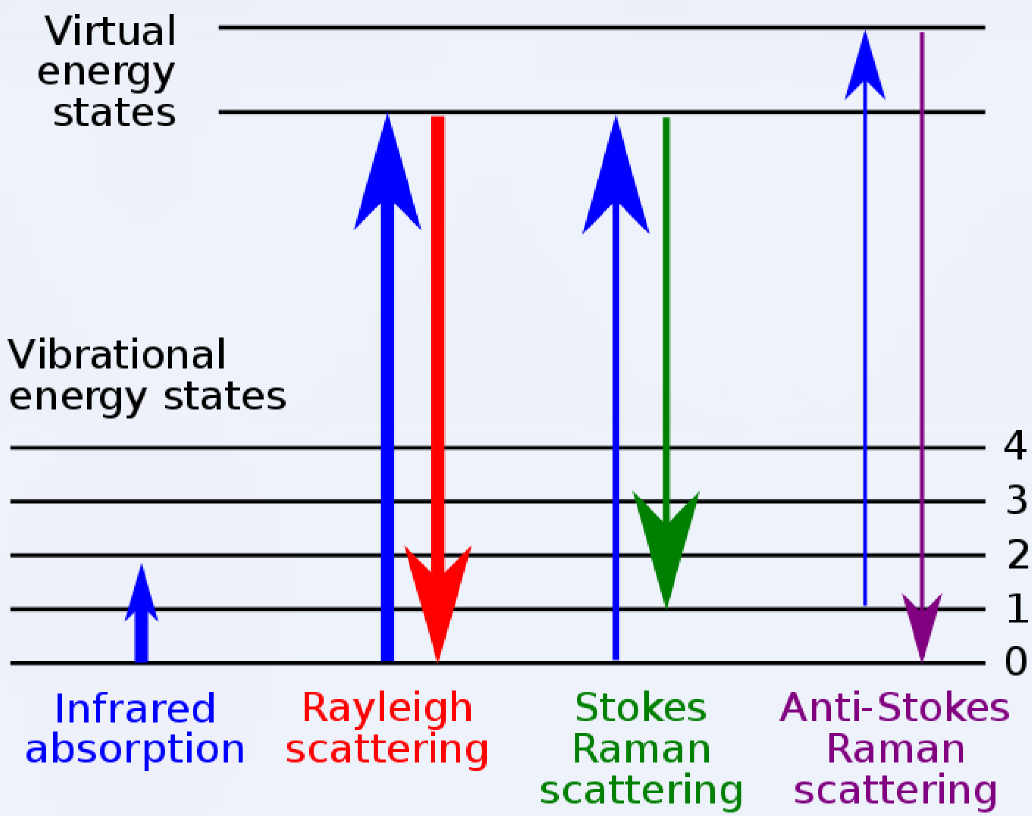
Probing methods

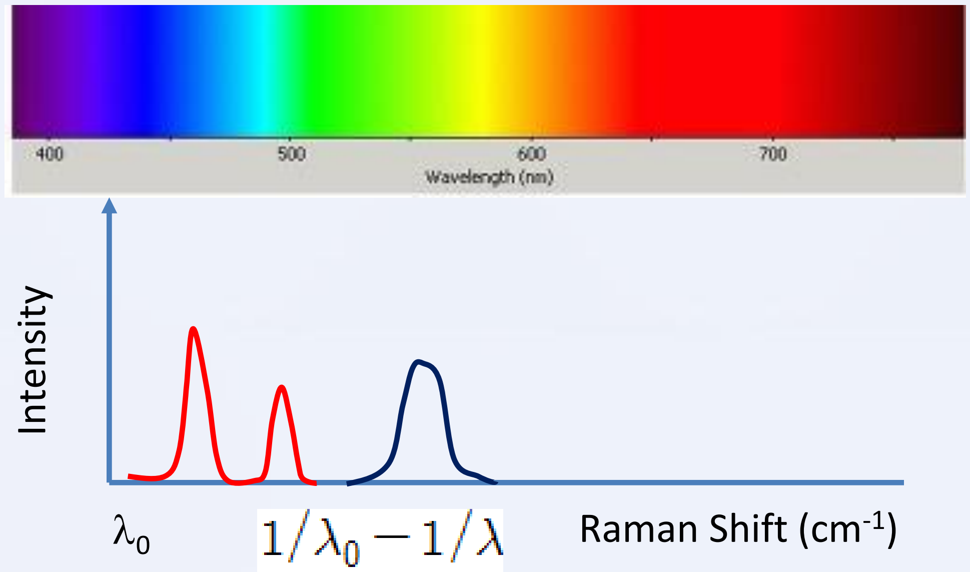


Raman Spectroscopy

Low energy excitation = $h(\nu - \nu')$

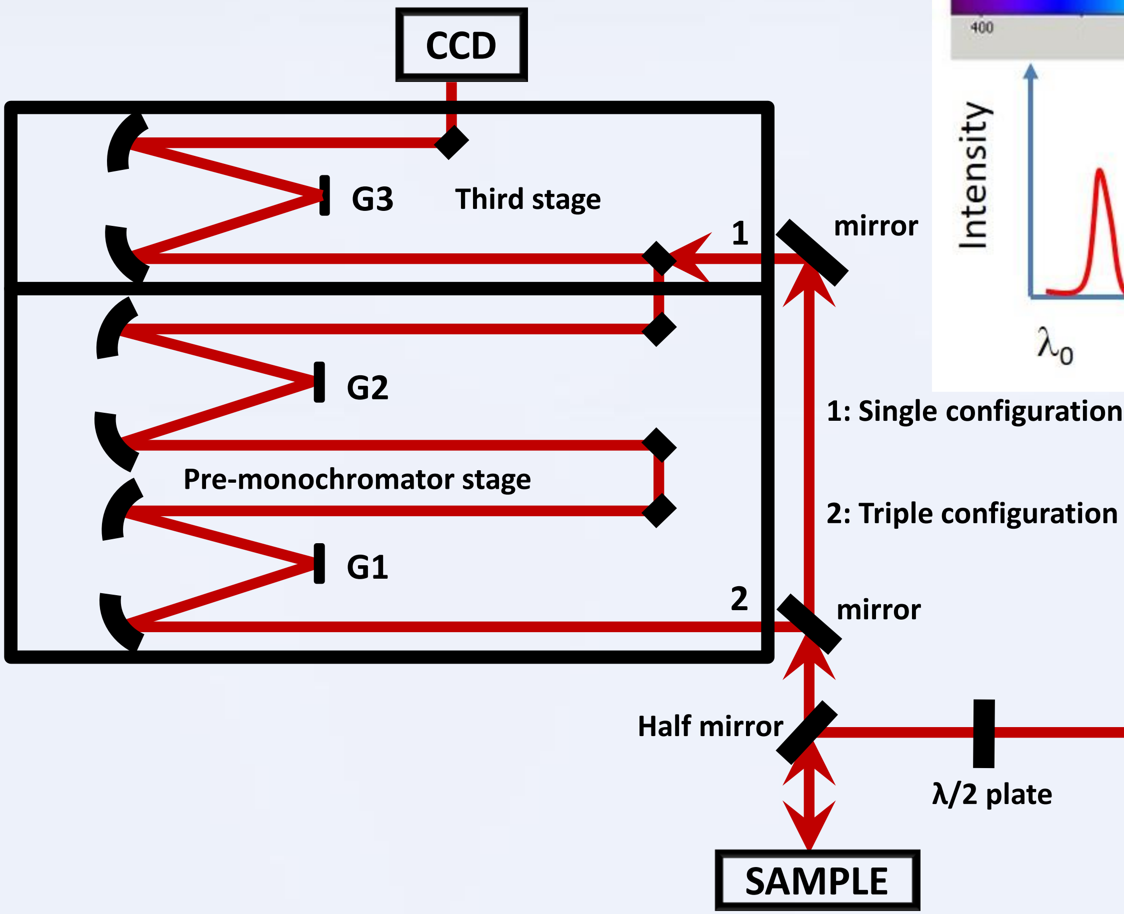


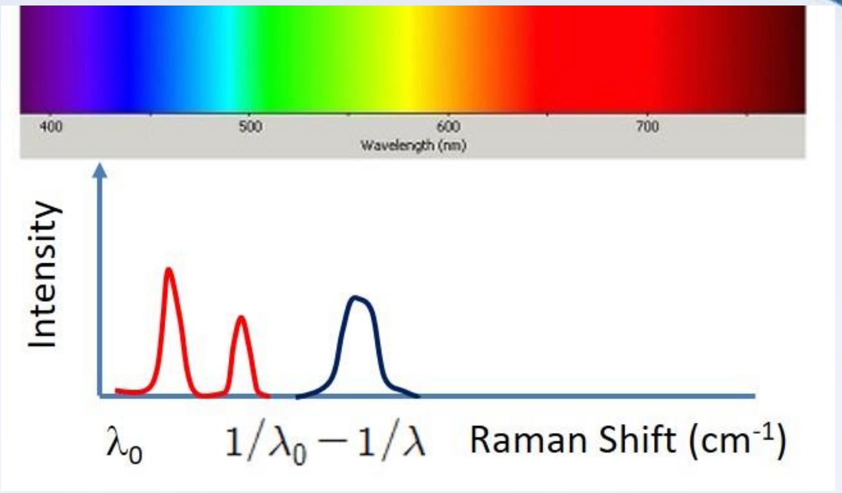
–from the Wikimedia Commons.–



400
500
600
700
Wavelength (nm)
Intensity
λ_0
$1/\lambda_0 - 1/\lambda$
Raman Shift (cm-1)

Raman Spectroscopy





Jobin Yvon T64000 spectrometer

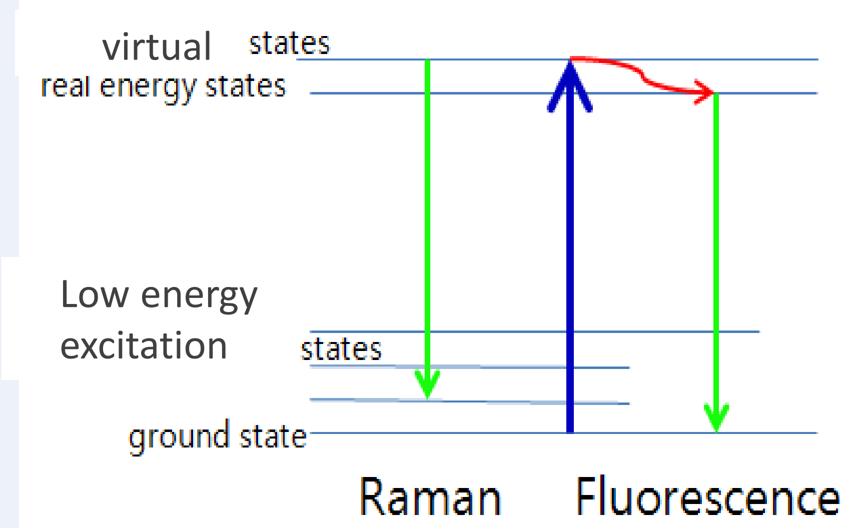
Raman Effect vs Fluorescence

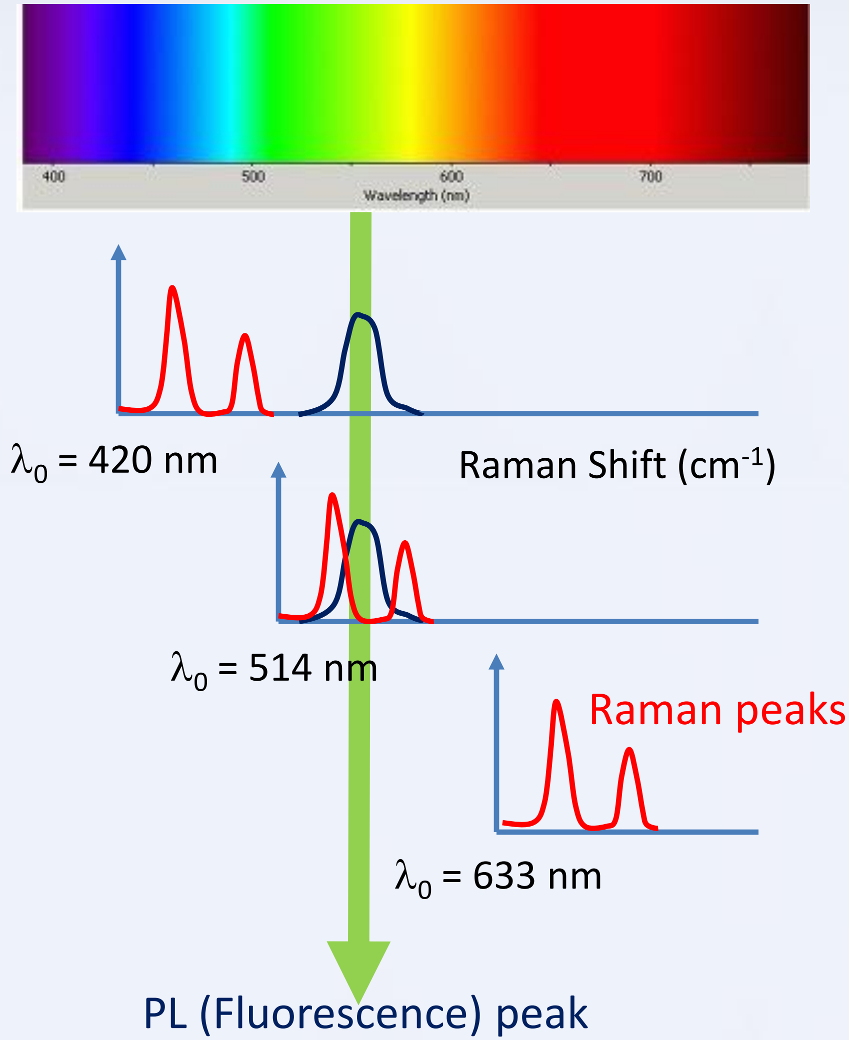
Raman spectroscopy

$h\nu \rightarrow h\nu'$; excitation = $h(\nu-\nu')$

Fluorescence spectroscopy

$h\nu \rightarrow h\nu'$; excitation = $h\nu'$





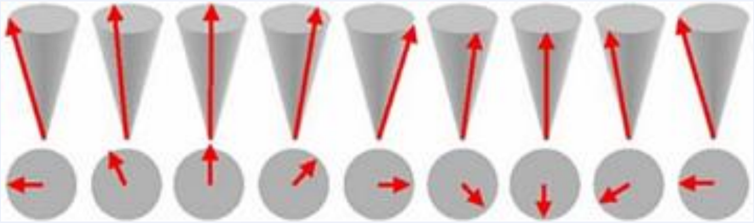
Raman spectroscopy can probe :

- Vibrational states
- Rotational states
- Electronic states
- Charge ordering (Superconducting gap, 2Δ)
- Spin ordering (spin waves)
- …

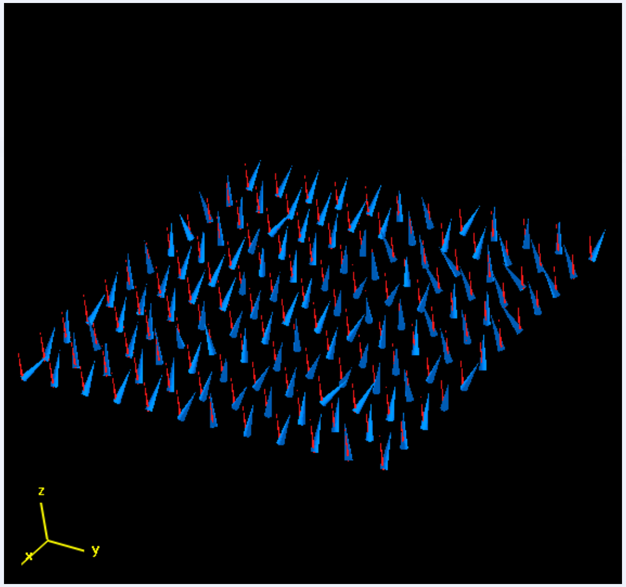
Quantized Spin Waves

A **magnon** is a quasiparticle, a collective excitation of the electrons spin structure in a crystal lattice. In the equivalent wave picture of quantum mechanics, a magnon can be viewed as a quantized spin wave. Magnons carry a fixed amount of energy and lattice momentum, and are spin-1, indicating they obey boson behavior.

- From Wikipedia, the free encyclopedia -



1-D Analogy



2-D Analogy

Quantum Memories

- Superconducting Nano devices
- Nuclear spin - decoherence time
- Atomic states - natural candidates

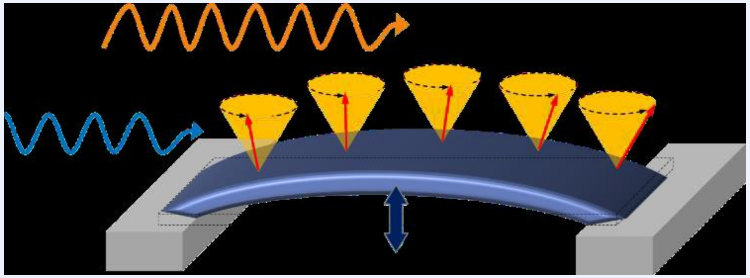
→ Require strong light-matter interaction

- Solid state systems = scalability, integration into existing technology

$Pr^{3+}:Y_2SiO_5$ crystal : solid-state spin-wave optical quantum memory

-Mustafa Gündoğan et al., Phys. Rev. Lett. 114, 230501 (2015)

Precession of Magnetic Moments – Spin Wave



Magneto-Mechanical Resonator

Adopted from the Talk of Cho, Sung Un, Department of Physics and Astronomy, Seoul National University (July 4, 2017)

Spin Wave

a reliable channel of
the light-matter interaction:

excitation/detection
(write/read) in
the Quantum Memories

0. Brief history of Raman studies of spin excitations in hexagonal RMnO$_3$ system

Spin excitations in hexagonal *R*MnO_3 (*R* = rare earths)

+ First found in hexagonal $HoMnO_3$ thin films, using 647 nm excitation source.

Raman scattering studies of the magnetic ordering in hexagonal $HoMnO_3$ thin films, Nguyen Thi Minh Hien, Xiang-Bai Chen, Luc Huy Hoang, D, Lee, S.-Y. Jang, T. W. Noh, and **In-Sang Yang**, Journal of Raman Spectroscopy 41, 983-988 (2010)

+ The spin excitations were resonant in very narrow range of excitation energy.

Resonant A(1) phonon and four-magnon Raman scattering in hexagonal $HoMnO_3$ thin film, Xiang-Bai Chen, Nguyen Thi Minh Hien, D Lee, S-Y Jang,T W Noh, and **In-Sang Yang**, New Journal of Physics 12, 073046 (2010)

+ The spin excitations were found in other $RMnO_3$ (R= rare earths).

Raman scattering studies of hexagonal rare-earth $RMnO_3$ (R = Tb, Dy, Ho, Er) thin films, Nguyen Thi Minh Hien, Su-Young Oh, Xiang-Bai Chen, D. Lee, S.-Y. Jang, T. W. Noh, and **In-Sang Yang**, Journal of Raman Spectroscopy 42, 1774-1779 (2011)

+ We could get the spin-exchange interaction integral J values from Raman!

Spin exchange interactions in hexagonal manganites $RMnO_3$ (R = Tb, Dy, Ho, Er) epitaxial thin films, Xiang-Bai Chen, Nguyen Thi Minh Hien, D. Lee, S.-Y. Jang, T. W. Noh, and **In-Sang Yang**, App.Phys.Lett. 99, 052506 (2011)

Magnons in hexagonal *R*MnO_3 (*R* = rare earths)

+ Spin excitations in Mn^{+3} sublattices of hexagonal *R*MnO_3 can be selectively excited!

-> Raman study is much more useful in studying the magnetic transitions due to changes in Mn-spin interactions than magnetization measurements.

"Study of spin-ordering and spin-reorientation transitions in hexagonal manganites through Raman spectroscopy", Xiang-Bai Chen, Nguyen Thi Minh Hien, Kiok Han, Ji-Yeon Nam, Nguyen Thi Huyen, Seong-Il Shin, Xueyun Wang, S. W. Cheong, D. Lee, T. W. Noh, N. H. Sung, B. K. Cho, and **In-Sang Yang**, Scientific Reports 5, 13366 (2015).

+ Spin excitations tell us about the spin-structural phase transition in hexagonal *R*MnO_3.

"Correlation between magnon and magnetic symmetries of hexagonal $RMnO_3$ (R = Er, Ho, Lu), Thi Minh Hien Nguyen, Thi Huyen Nguyen, Xiang-Bai Chen, Yeonju Park, Young Mee Jung, D. Lee, T.W. Noh, Sang-Wook Cheong, and **In-Sang Yang**, Journal of Molecular Structure 1124, 103-109 (2016).

+ We suggested the spin flip mechanism in hexagonal $LuMnO_3$ single crystal.

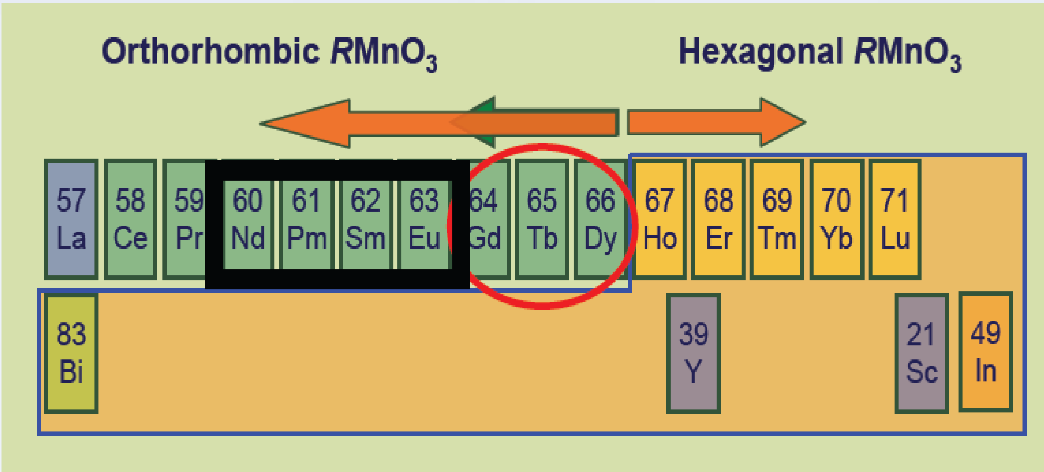
"Spin wave and spin flip in hexagonal $LuMnO_3$ single crystal", Xiang-Bai Chen, Peng-Cheng Guo, Nguyen Thi Huyen, Seung Kim, **In-Sang Yang**, Xueyun Wang, Sang-Wook Cheong, Appl. Phys. Lett. **110**, 122405 (2017).

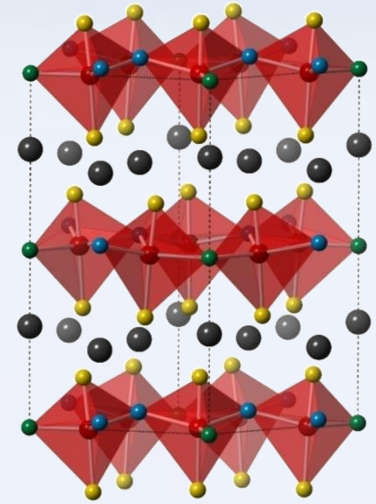
+ Dr. Hien investigated two-magnons in other AIAO material ($Cd_2Os_2O_7$)

"Two-Magnon Scattering in 5d All-In-All-Out Pyrochlore Magnet $Cd_2Os_2O_7$", Nguyen Thi Minh Hien, Luke J. Sandilands, C.H. Sohn, C. H. Kim, Aleksander L Wysocki, **In-Sang Yang**, S. J. Moon, Jae-Hyeon Ko, Z. Hiroi, J. Yamaura, and Tae Won Noh, Nature Communications 8, 251 (2017).

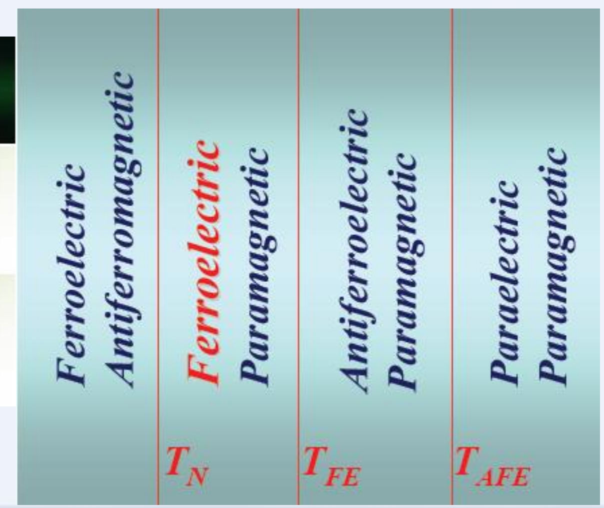
-> The spin excitations are very important, useful quantity !

I. Review of $RMnO_3$: *why hexagonal $RMnO_3$?*

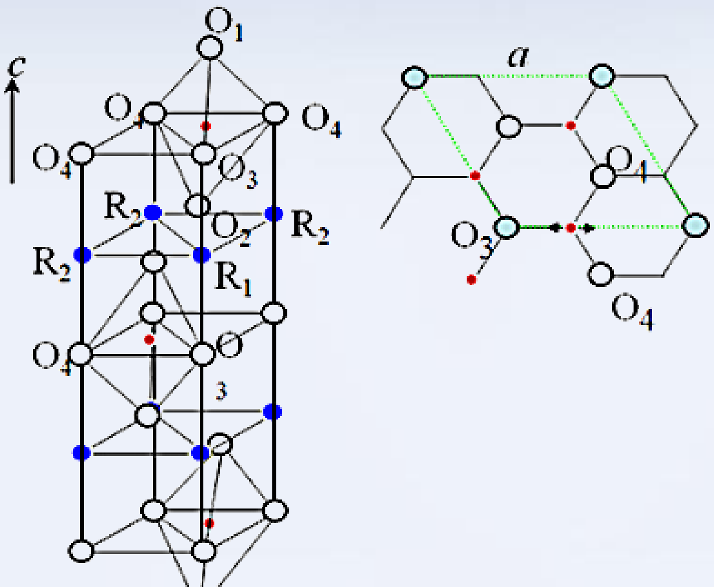




	Ferroelectric T_{FE} (K)	P_r ($\mu C/cm^2$)	Anti-FM T_N (K)
Ortho – *R*MnO_3 (*R* = Dy, Tb, Gd)	~ 24	~ 0.2	~ 40
Hexa – *R*MnO_3 (*R* = Ho , Y, …)	> 900	~ 5.6	~ 100



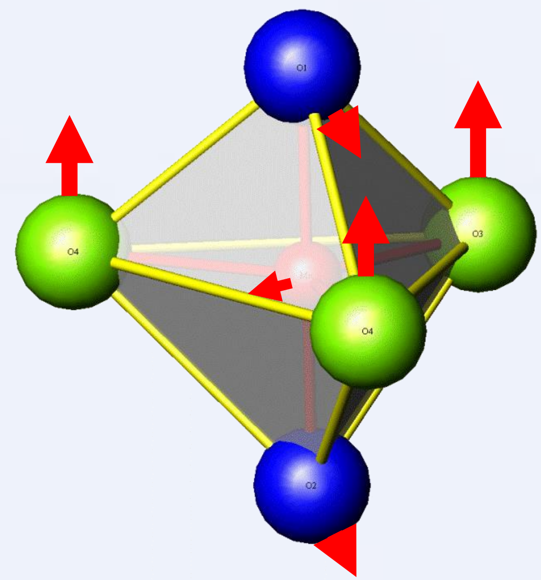
I. Review of $RMnO_3$: *Structure & Raman active modes*

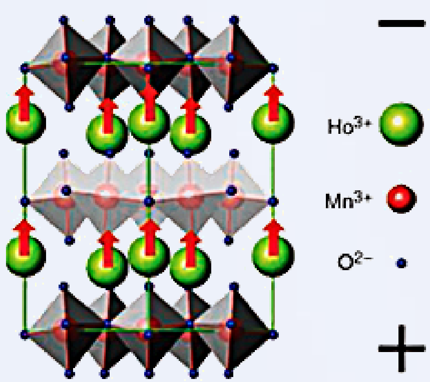


(a)

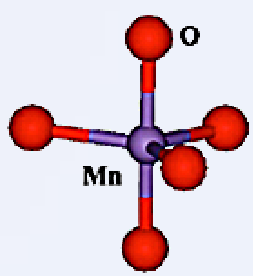
Space group: $P6_3cm$

The unit cell contains
- Layers of corner sharing MnO_5 bipyramids
- O3 and O4 : triangular base
- O1 and O2 : apical sites.





(b)



(c)

$$\Gamma = 10A_1 + 5A_2 + 10B_1 + 5B_2 + 15E_1 + 15E_2$$

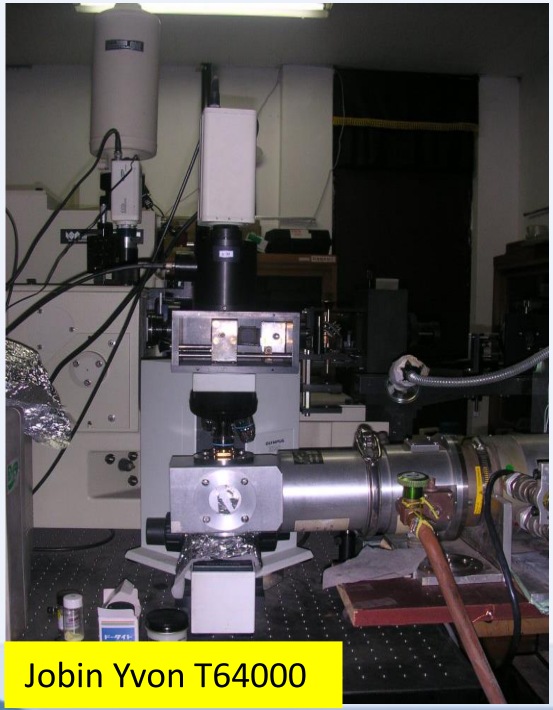
Raman active phonon : $9A_1 + 14E_1 + 15E_2$

II. Samples and Experiments: ***Raman experiments***

Hexagonal $HoMnO_3$ and $ErMnO_3$ thin films: were grown on Pt (111)// Al2O3 (0001) substrates by laser ablation method. All the thin films were grown epitaxially with their *c* axis perpendicular to the film surface

Hexagonal $LuMnO_3$ single crystal was grown using the traveling floating zone method. Platelet single crystal sample was cleaved perpendicular to the *c* axis.

Raman experiments



+ Objective lenses: ×50 ultra long working distance (ULWD)

+ Focus length: 8mm.

A closed-cycle helium cryostat was used to vary the sample temperatures from 13 to 300K.

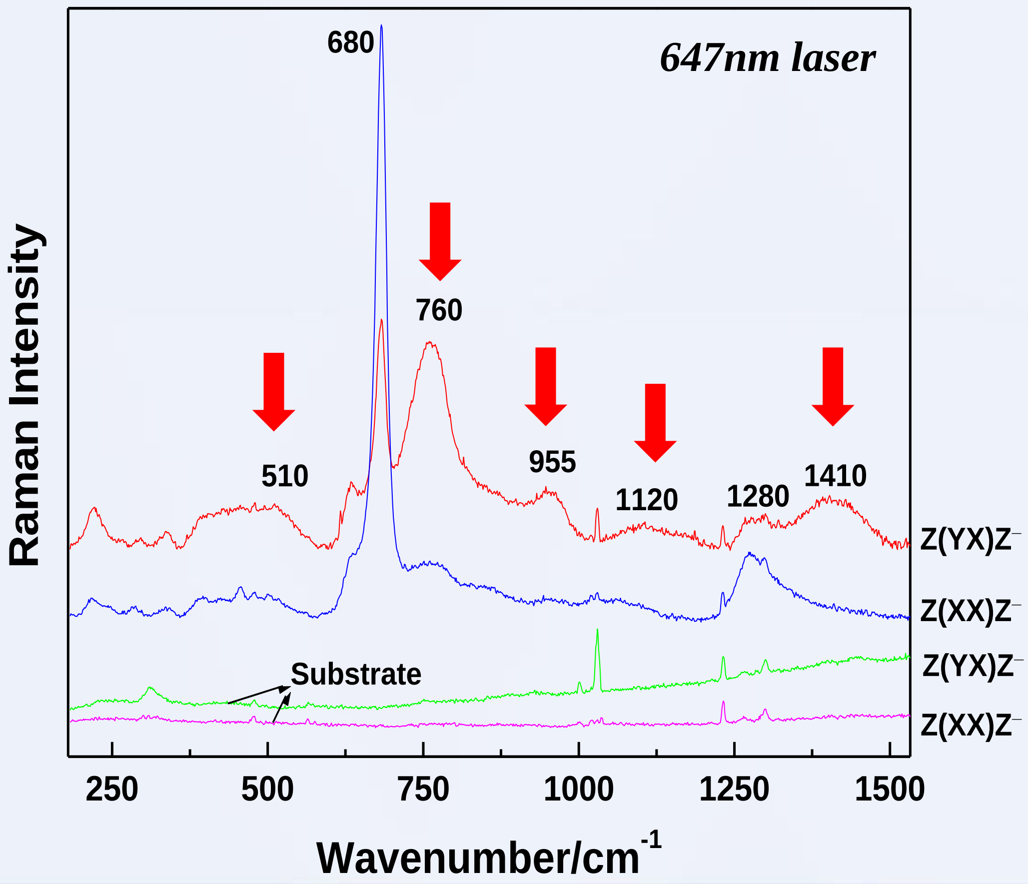
1. The magnetic ordering in hexagonal $HoMnO_3$ thin film

1. Raman scattering studies of the magnetic ordering in hexagonal $HoMnO_3$ thin films, Nguyen Thi Minh Hien, Xiang-Bai Chen, Luc Huy Hoang, D, Lee, S.-Y. Jang, T. W. Noh, and In-Sang Yang, Journal of Raman Spectroscopy 41, 983-988 (2010)

2. Resonant A(1) phonon and four-magnon Raman scattering in hexagonal $HoMnO_3$ thin film, Xiang-Bai Chen, Nguyen Thi Minh Hien, D Lee, S-Y Jang,T W Noh, and In-Sang Yang, New Journal of Physics 12, 073046 (2010).

III. Raman results: *Spin excitation peaks*

Raman spectra of hexagonal $HoMnO_3$ and Pt(111)//Al_2O_3 (0001) substrate at 13 K in different configurations.



+ 680cm^{-1}: A_1 phonon
+ Broad peak 1280 cm^{-1}: 2^{nd} order of A_1 phonon

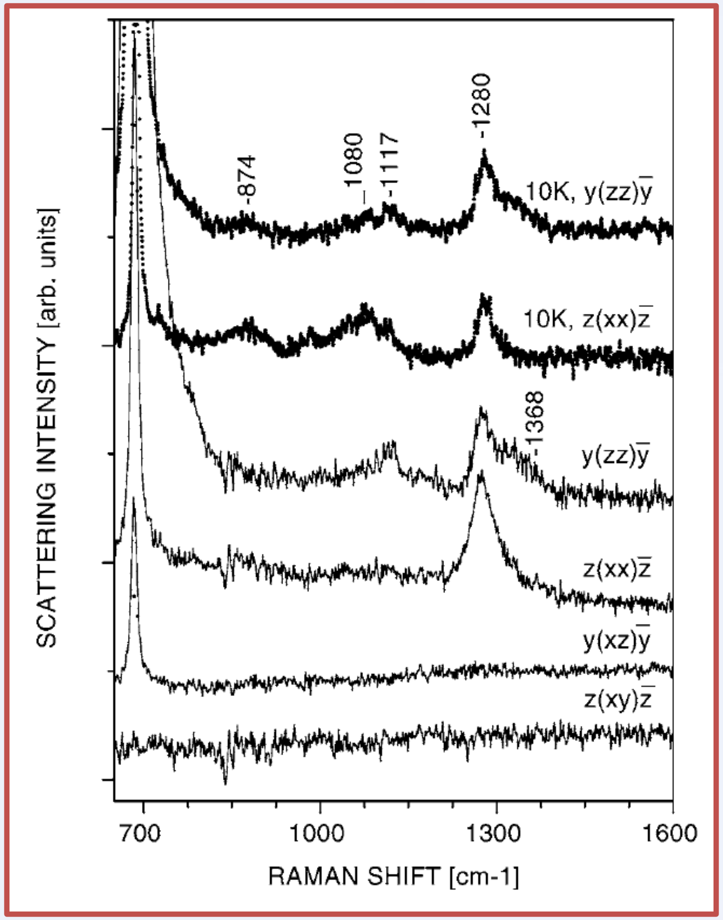
+ Several broad peaks : ~510, ~760, ~ 955,~ 1120 and ~1410 cm^{-1}

- cross polarization only!

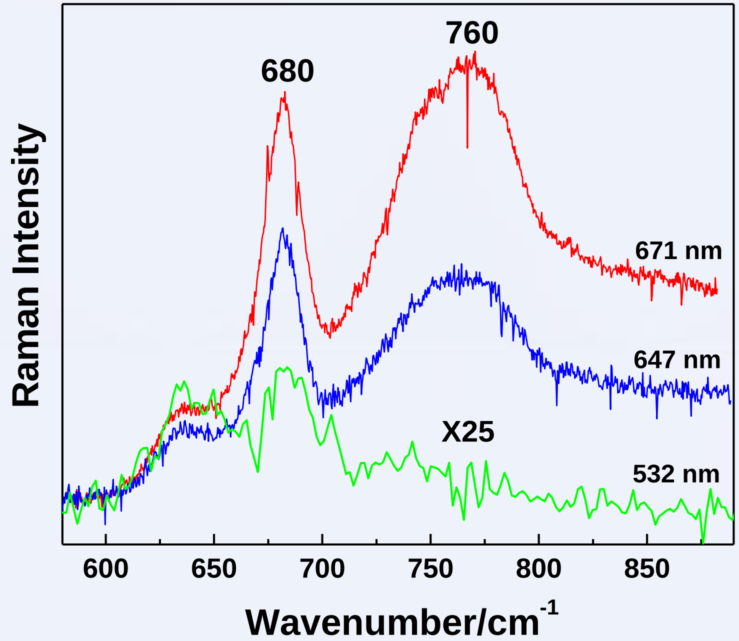
Magnon ??

$HoMnO_3$, $\lambda_{exc=}$514.5nm

***J. Phys.: Condens. Matter*, 16, 809 (2004).**



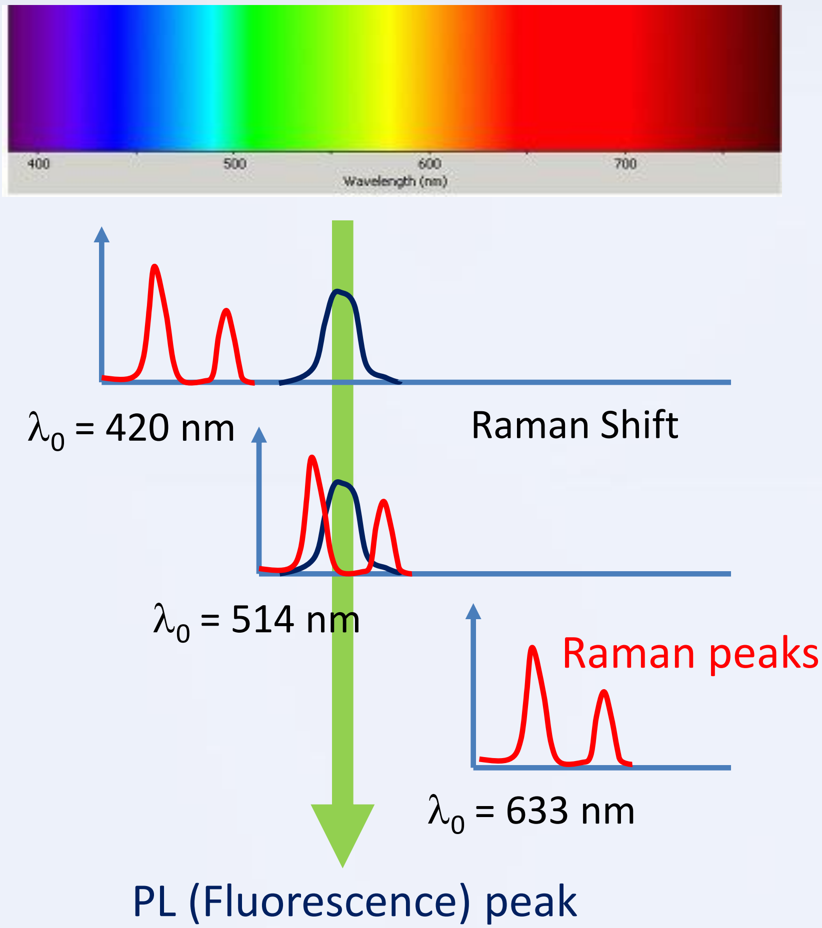
In cross polarization scattering @ 13 K



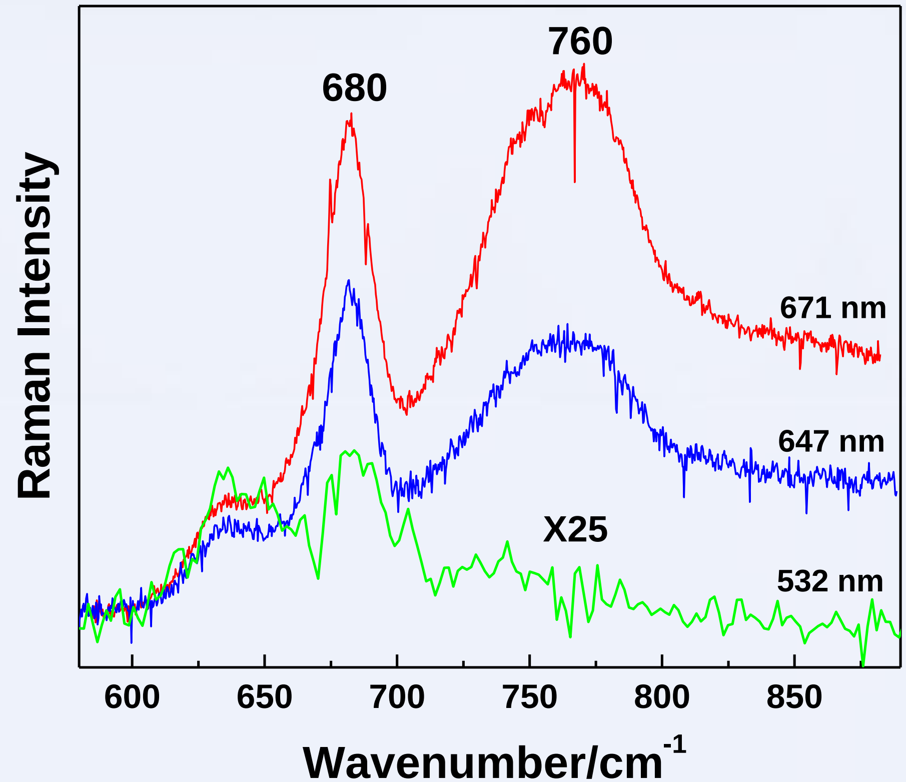
Confirms:

+ Raman origin, not PL!

+ Strongly resonant at 671nm (~1.8 eV)



400
500
600
700
Wavelength (nm)
λ_0 = 420 nm
Raman Shift
λ_0 = 514 nm
Raman peaks
λ_0 = 633 nm
PL (Fluorescence) peak

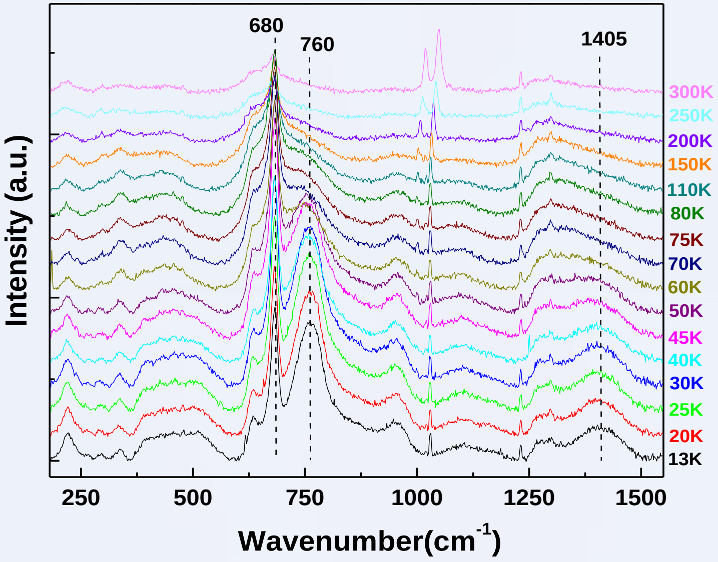


760
680
671 nm
647 nm
X25
532 nm
Raman Intensity
600
650
700
750
800
850
Wavenumber/cm^{-1}

III. Raman results: *Spin excitation peaks*

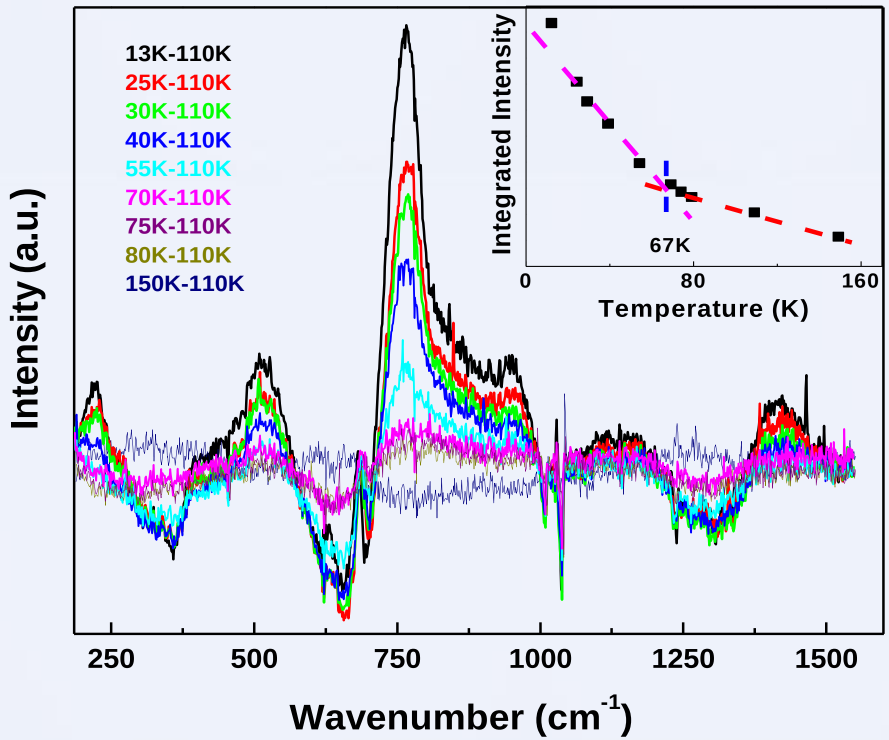
T dependence-Raman spectra of a hexagonal $HoMnO_3$ – cross polarization configurations

$z(yx)\bar{z}$



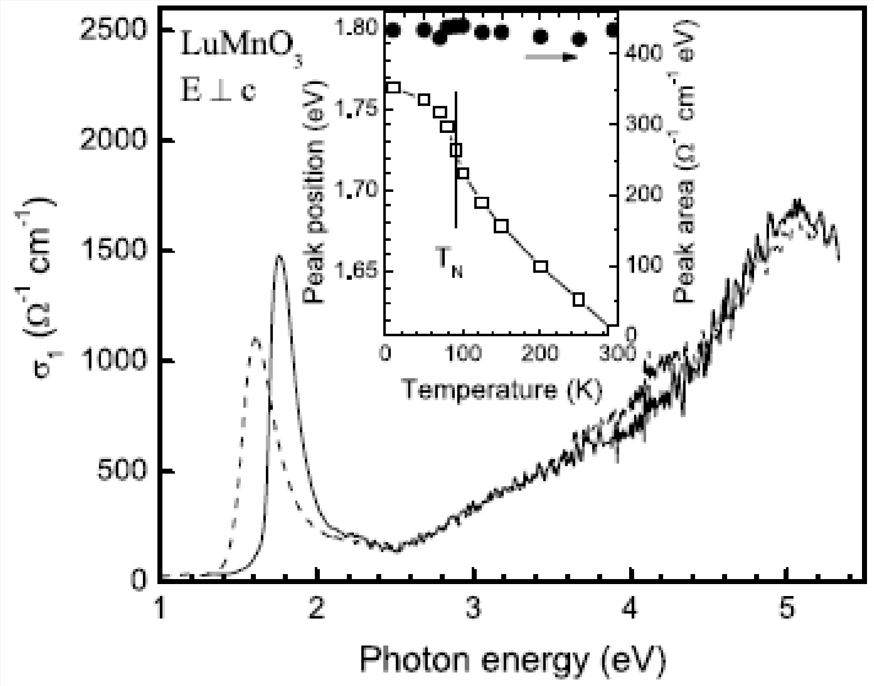
T↗: these broad peaks decrease > the phonon modes, and are disappearing above T_N

T dependence of the difference spectra



⇒ shows an inflection point at T=67 K ~T_N

⇒ **Related with Magnetic Ordering**

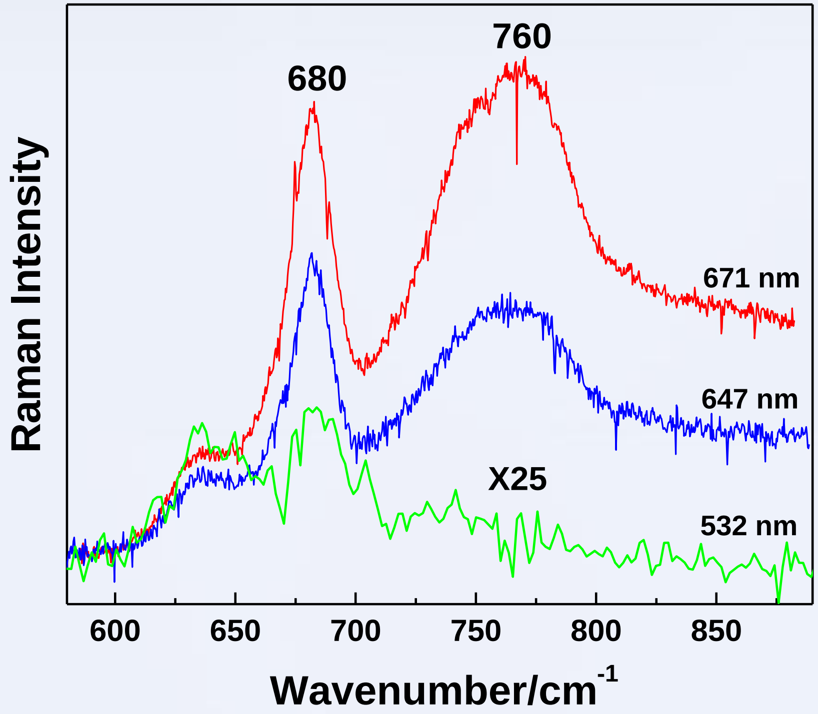


The electronic conductivity of LuMnO3.

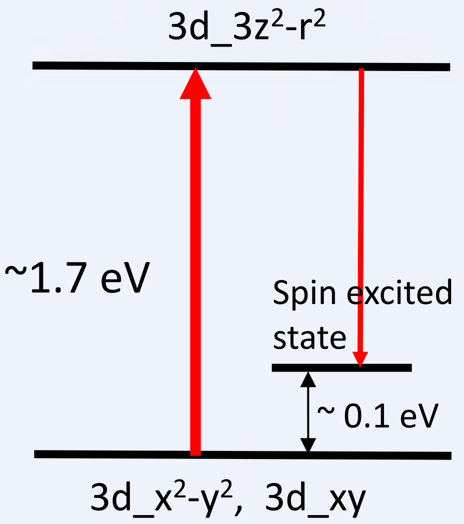
Phys. Rev. Lett. **91**, 027203 (2003)

- Peak at ~ 1.7 eV: on-site Mn *d*–*d* transition.
- Broad band centered at ~ 5 eV: charge transfer transition from the hybridized oxygen *p* levels to the Mn *d* levels.
- The on-site Mn *d*–*d* transition at ~ 1.7 eV shifts ~ 0.15 eV with temperature.
- The shift is mainly caused by the effects of the exchange interaction between the Mn ions.

Resonant effect



671nm	1.85eV
647nm	1.92eV
532nm	2.33eV



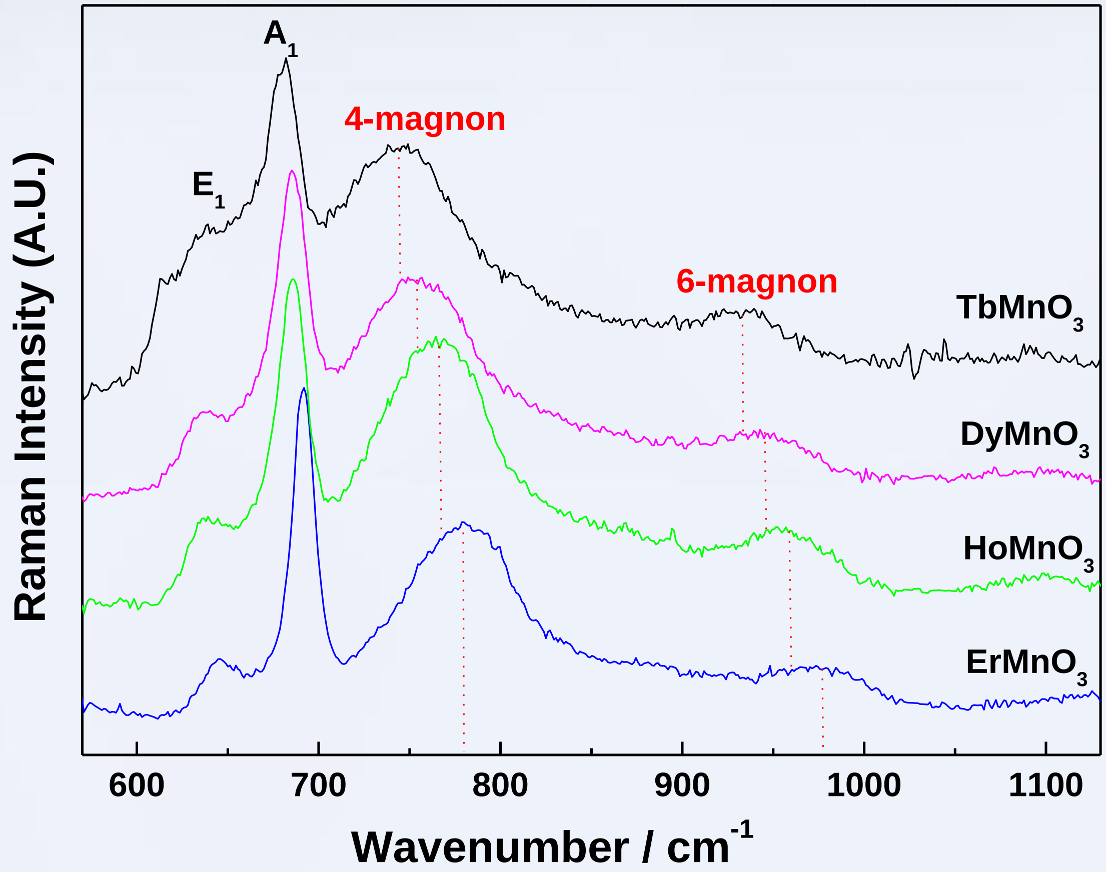
Spin excitation peak (760 cm^{-1}) resonant effect is related to Mn d-d transition.

Xiang-Bai Chen *et al.* ,*New J. Phys.*, **12,** 073046(2010).
Xiang-Bai Chen *et al. Appl. Phys. Lett.* **110**, 122405 (2017).

2. Rare-earth *R* dependence of *R*MnO_3 (*R*=Tb, Dy, Ho, Er) thin films

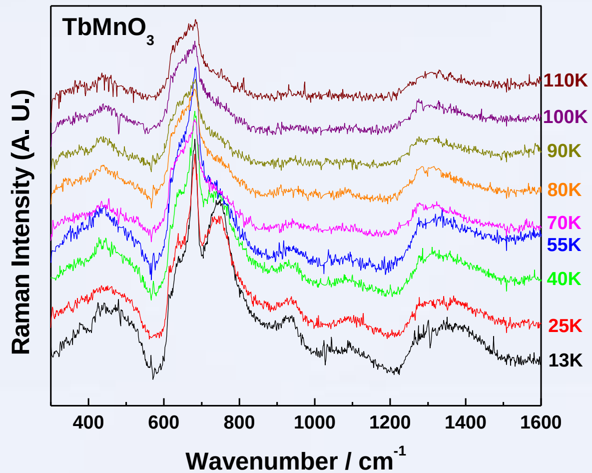
3. Raman scattering studies of hexagonal rare-earth *R*MnO_3 (*R* = Tb, Dy, Ho, Er) thin films, Nguyen Thi Minh Hien, Su-Young Oh, Xiang-Bai Chen, D. Lee, S.-Y. Jang, T. W. Noh, and In-Sang Yang, Journal of Raman Spectroscopy 42, 1774-1779 (2011).

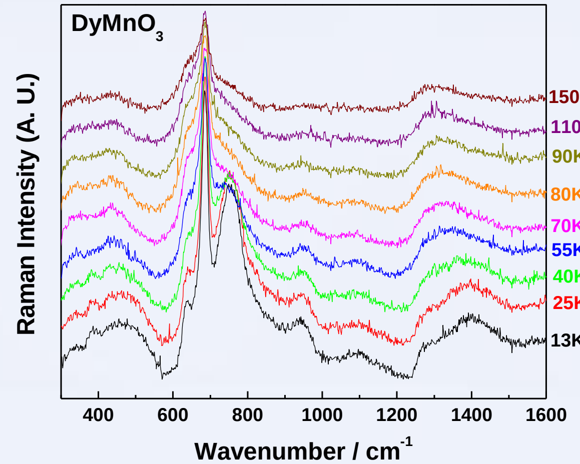
4. Spin exchange interactions in hexagonal manganites *R*MnO_3 (*R* = Tb, Dy, Ho, Er) epitaxial thin films, Xiang-Bai Chen, Nguyen Thi Minh Hien, D. Lee, S.-Y. Jang, T. W. Noh, and In-Sang Yang, App.Phys.Lett. 99, 052506 (2011).

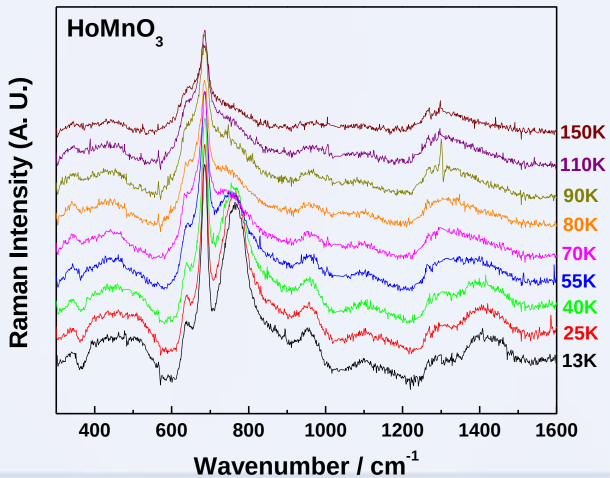


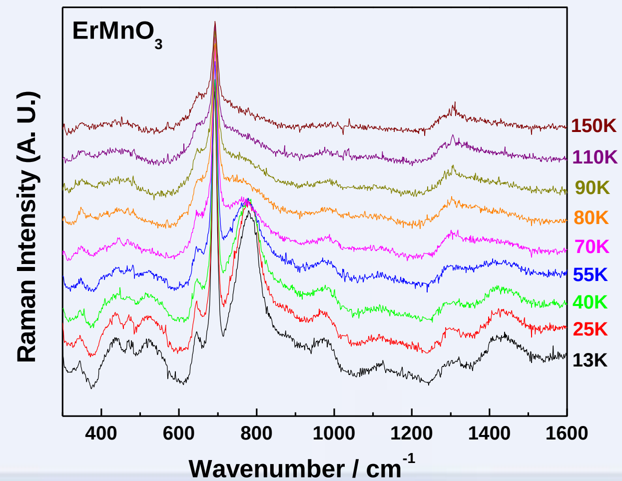
Polarized Raman spectra of hexagonal $RMnO_3$ (R = Tb, Dy, Ho, Er) thin films at 13 K obtained in the Z(XY)Z- ***configuration.***

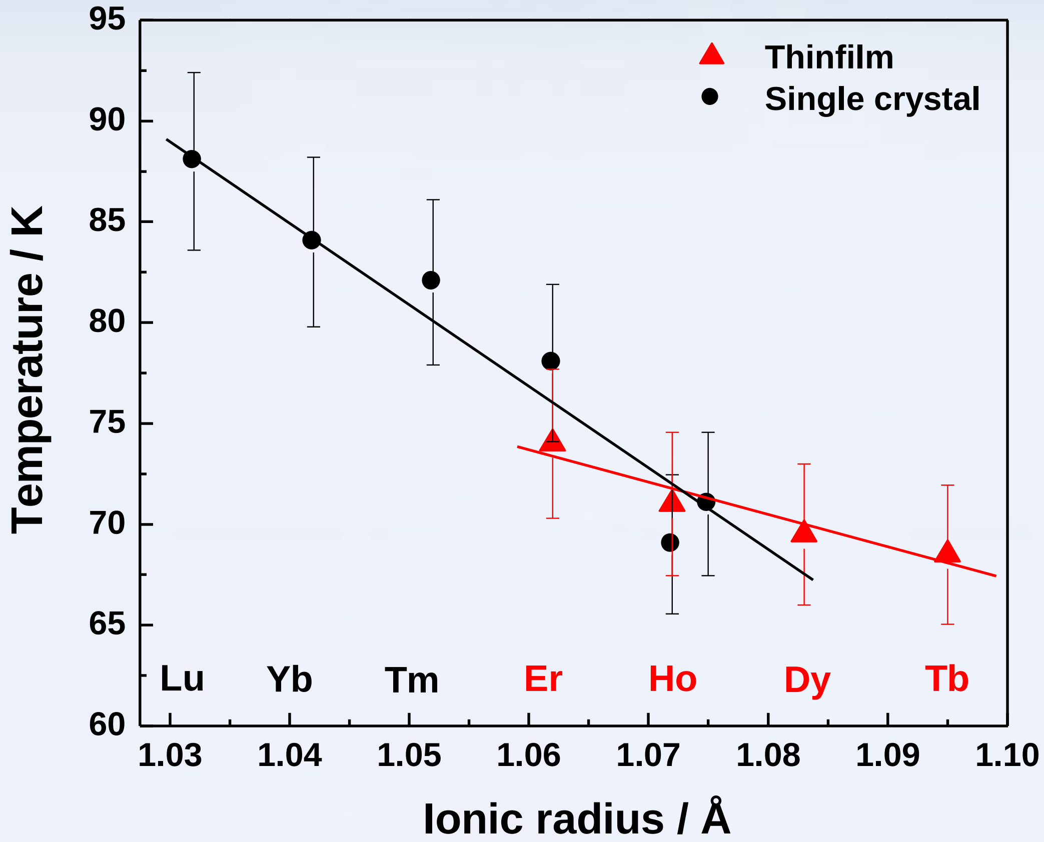
T dependent (13K – 150K) Raman spectra of hexagonal $RMnO_3$ (R = Tb, Dy, Ho, Er) thin films obtained in the Z(XY)Z- configuration.







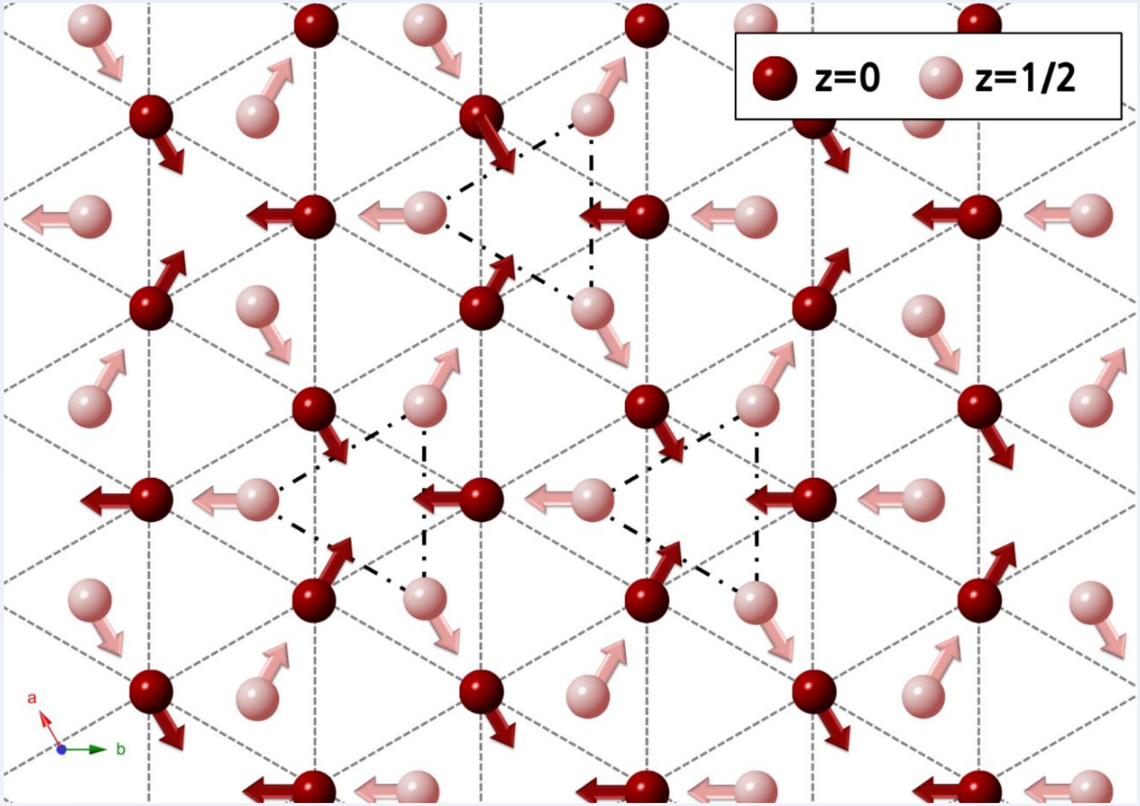




T_N - *R* dependence: our thin films < single crystals.
=> the lattice constant *a* varies slower with the radius of *R* ion comparing with the single crystals

Fig 8: The R ionic radius dependence of T_N for our thin films and the single crystals

Mn-plane **(@ $T < T_N$)**



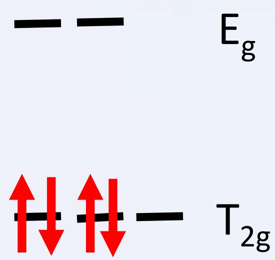
Below T_N the Mn spins order antiferromagnetically in a noncollinear 120° spin structure. (All–In–All–Out structure)

Spin states of some transition ions

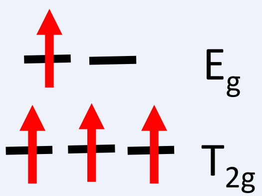
3d level electron TM ions	3d^4 Mn^{3+}	3d^5 Mn^{2+}, Fe^{3+}	3d^6 Fe^{2+}	3d^7 Co^{2+}, Ni^{3+}
Weak Crystal Field High Spin State	S=2	S=5/2	S=2	S=3/2
Strong Crystal Field Low Spin State	S=0	S=1/2	S=0	S=1/2

Mn^{3+} ($3d^4$)

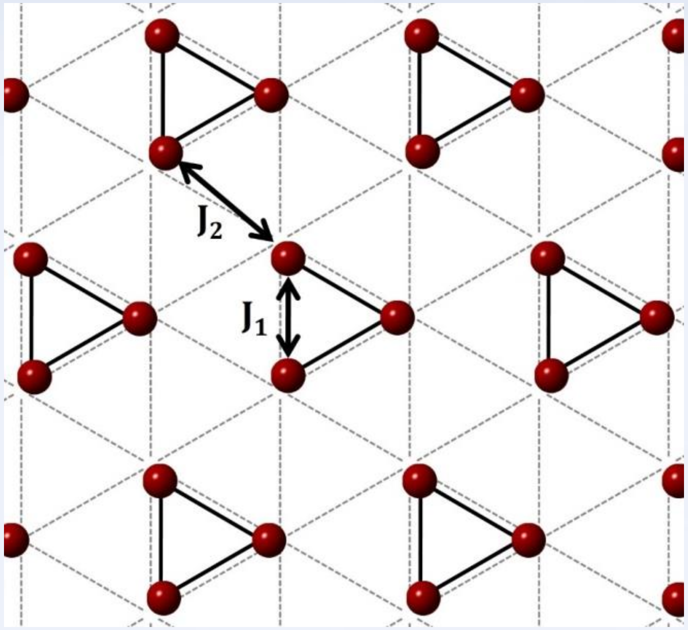
Strong Crystal Field
Low Spin State
S=0



Weak Crystal Field
High Spin State
S=2



III. Raman results: *Spin excitation peaks*



$T < T_N$

$$H = J_1 \sum_{<i,j>} (S_i \cdot S_j) + J_2 \sum_{<i,k>} (S_i \cdot S_k)$$

J_1: intratrimer Mn-Mn spin interaction
J_2: intertrimer Mn-Mn spin interaction

The 4-spin flipping magnon

4-magnon

spin flipping of 3 Mn^{3+} ions in 1 triangle and 1 Mn^{3+} ion in the neighboring triangle

$13J_1 + 26J_2$: **96.2meV**
~770 cm^{-1}

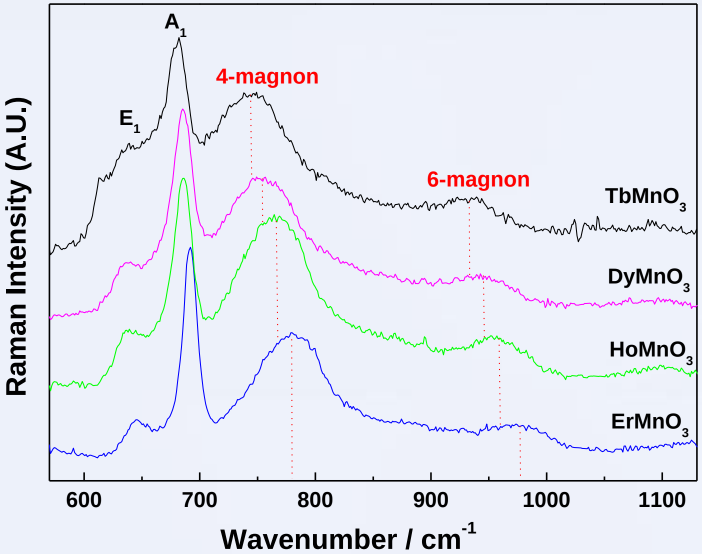
The 6-spin flipping magnon

6-magnon

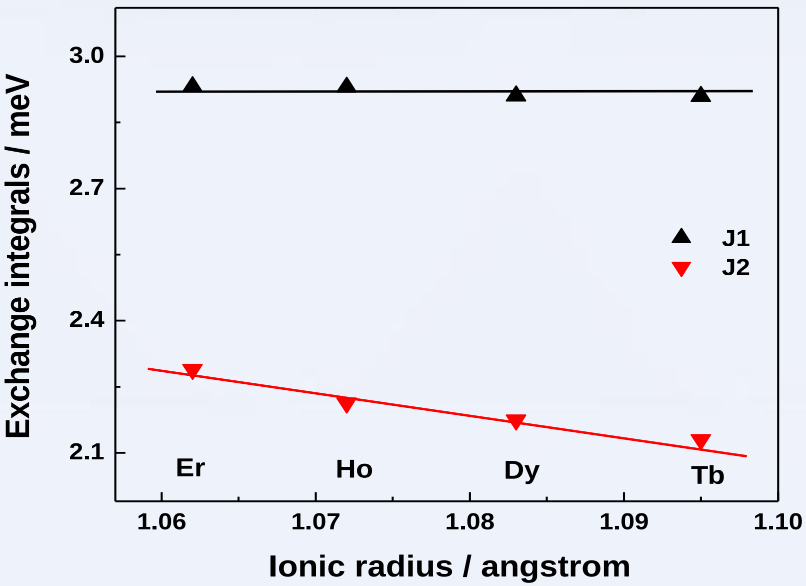
spin flipping of 6 Mn^{3+} ions in 2 neighboring triangle

$18J_1+34J_2$: **129.2meV**
~1000 cm^{-1}

Raman spectra of hexagonal $RMnO_3$ (R = Tb, Dy, Ho, Er) thin films-13 K- cross configuration.



The R dependence J_1 and J_2 of hexagonal $RMnO_3$.



J_2 decreases systematically when the R ionic radius increases

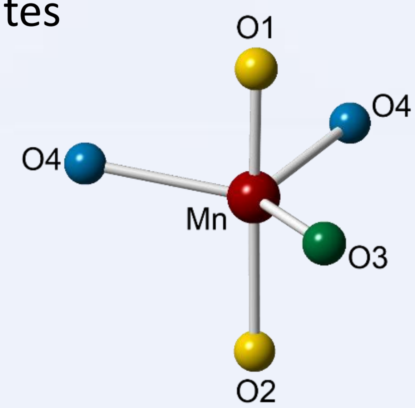
J_1 is nearly independent of R ionic radius.

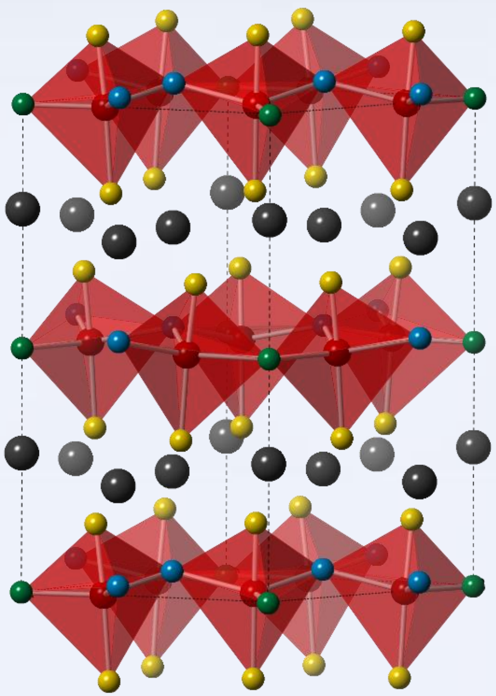
➡ Raman Spectroscopy is an easier method than Neutron Scattering !

3. Spin excitations in Ga-doped hexagonal $HoMnO_3$ thin films

Sample - Hexagonal $HoMnO_3$

- Hexagonal $HoMnO_3$
  - Space group: $P6_3cm$
  - Layers of corner-sharing MnO_5 bipyramids
  - O3 and O4 : triangular base
  - O1 and O2 : apical sites

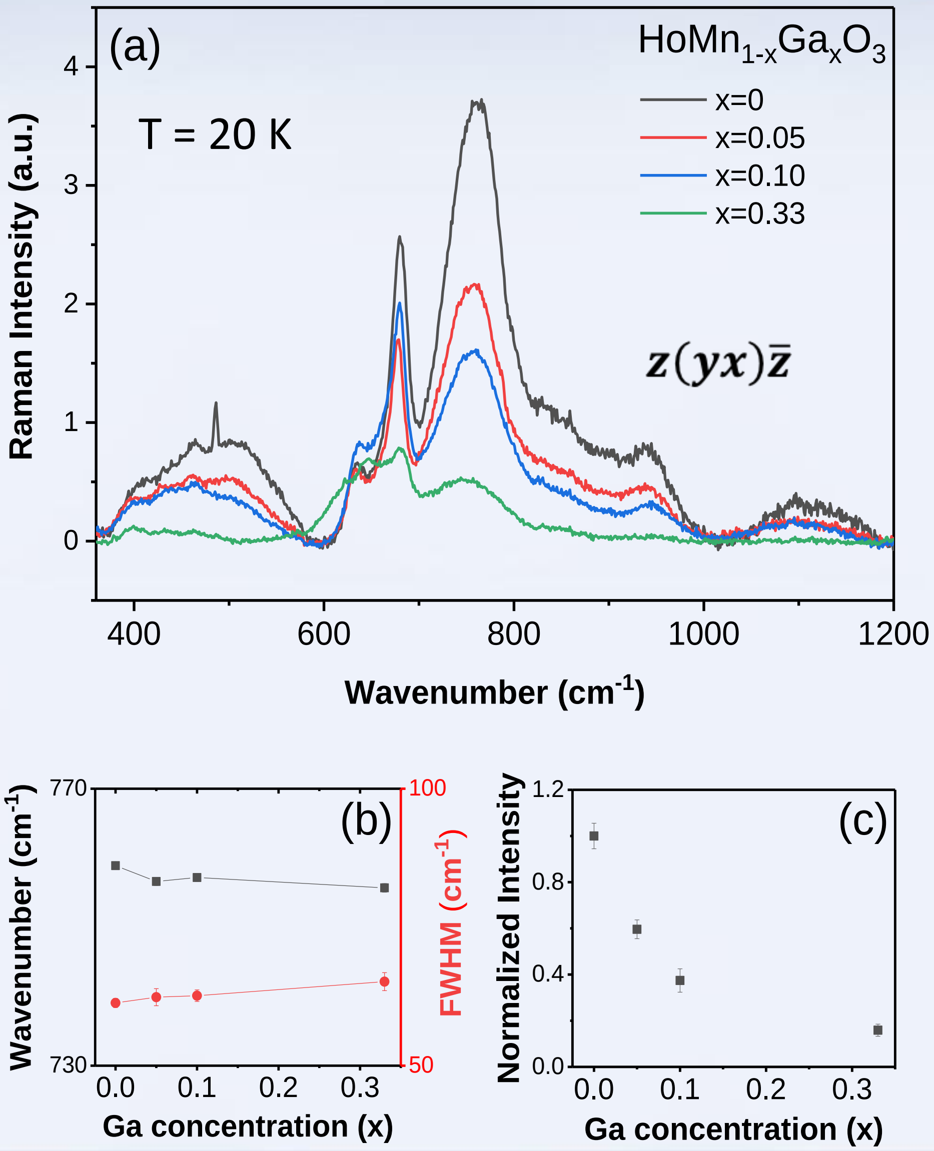




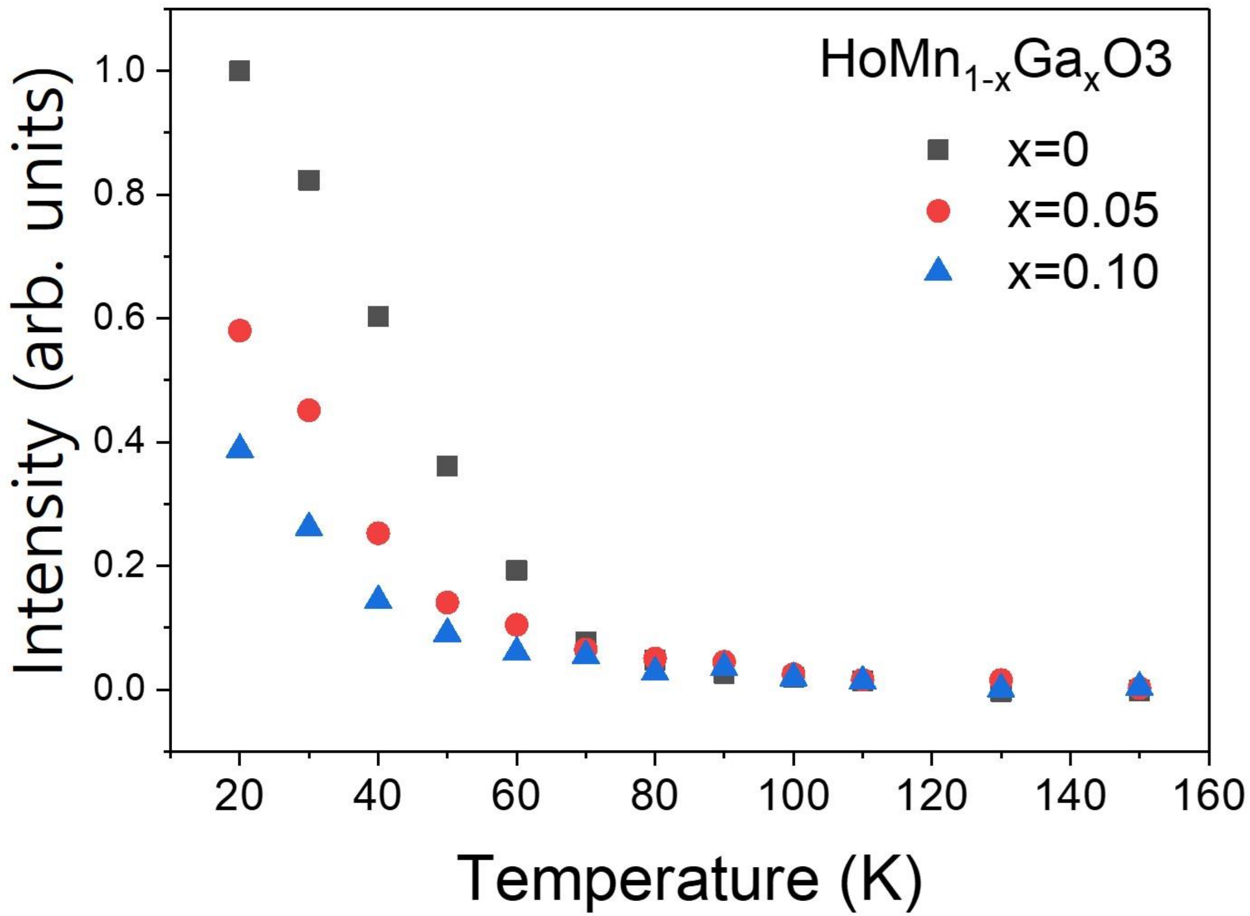
- $HoMn_{1-x}Ga_xO_3$ thin film (x=0, 0.05, 0.1 and 0.33)
- The samples were grown on Pt(111)//Al2O3 (0001) substrates by pulsed laser deposition techniques.

Results

- Spin excitation energy (peak position) and FWHM values are weakly affected.
- Spin excitation intensity has ~40% and 60% decrease for 5% and 10% Ga doping, respectively.

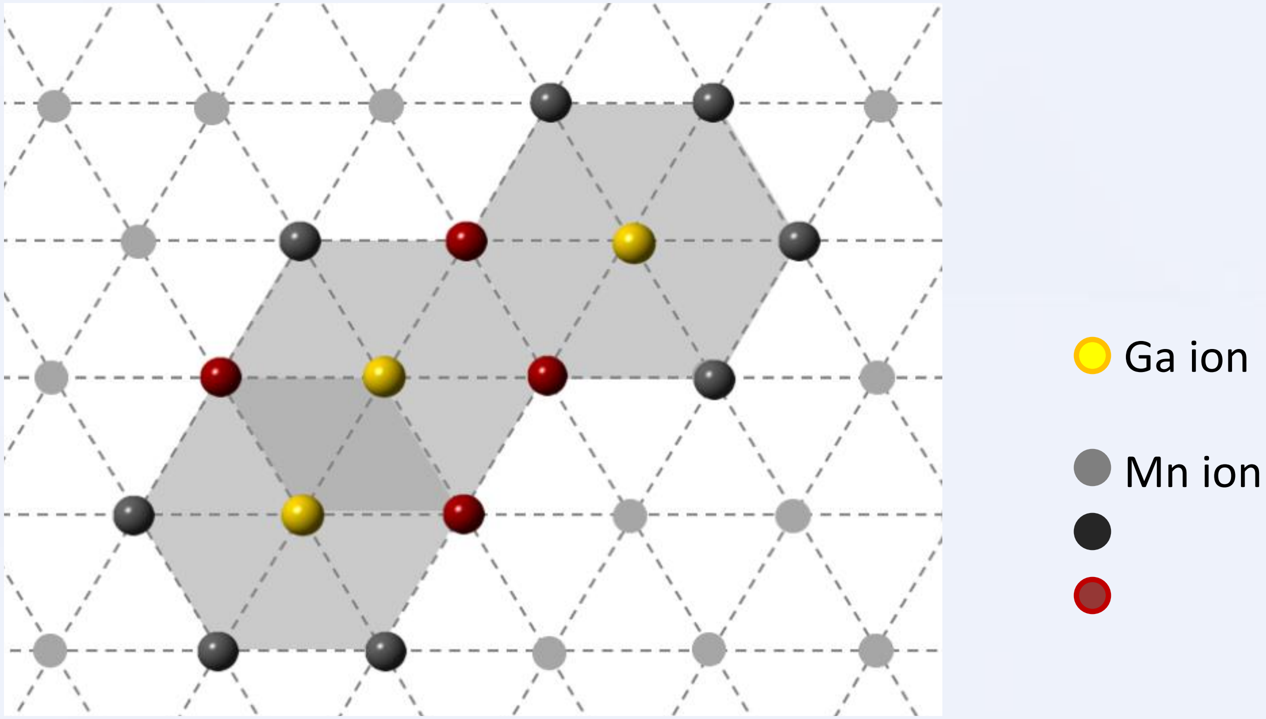


Results



HoMn1-xGaxO3
x=0
x=0.05
x=0.10
Intensity (arb. units)
Temperature (K)
0.0
0.2
0.4
0.6
0.8
1.0
20
40
60
80
100
120
140
160

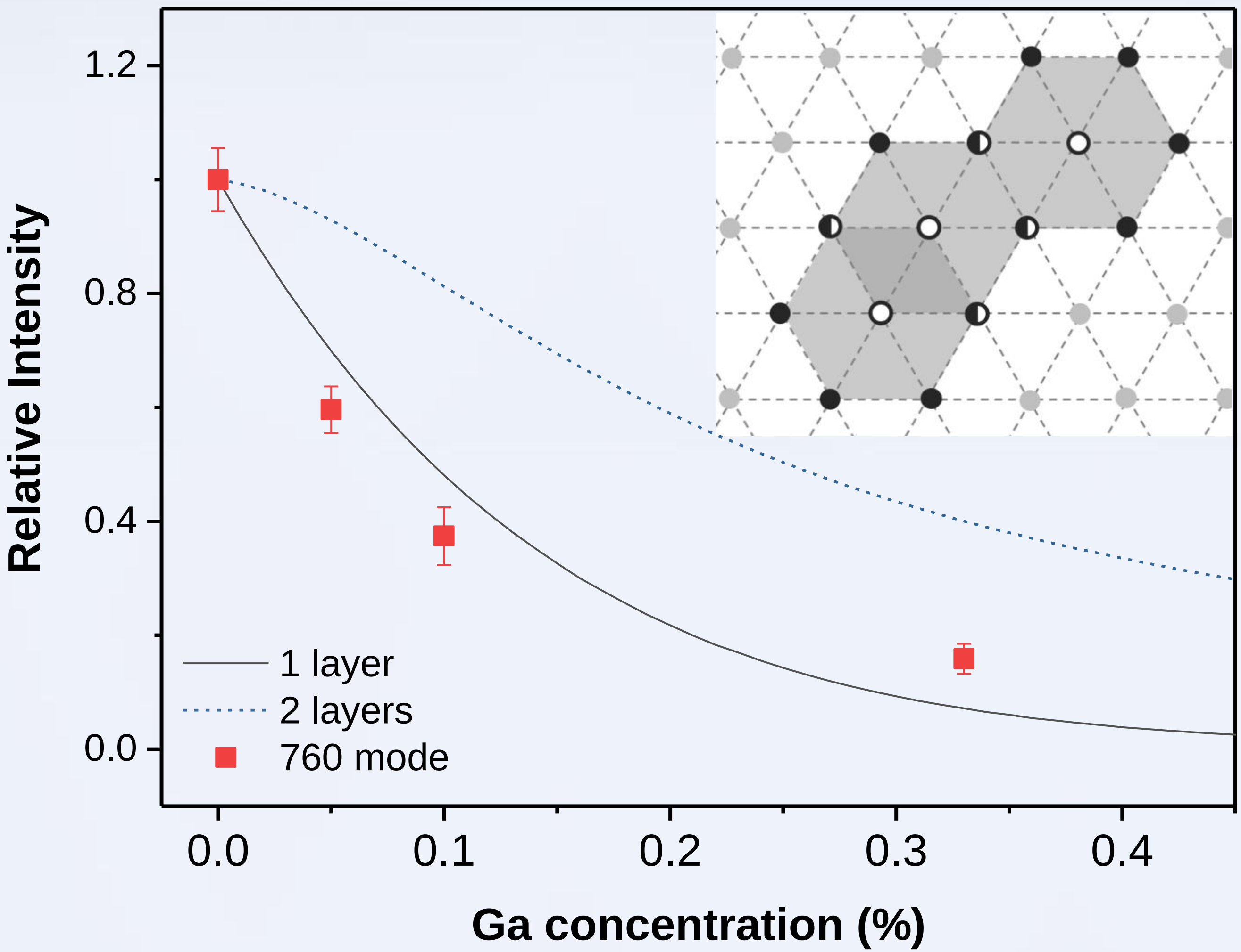
A Mn-Mn triangular network :



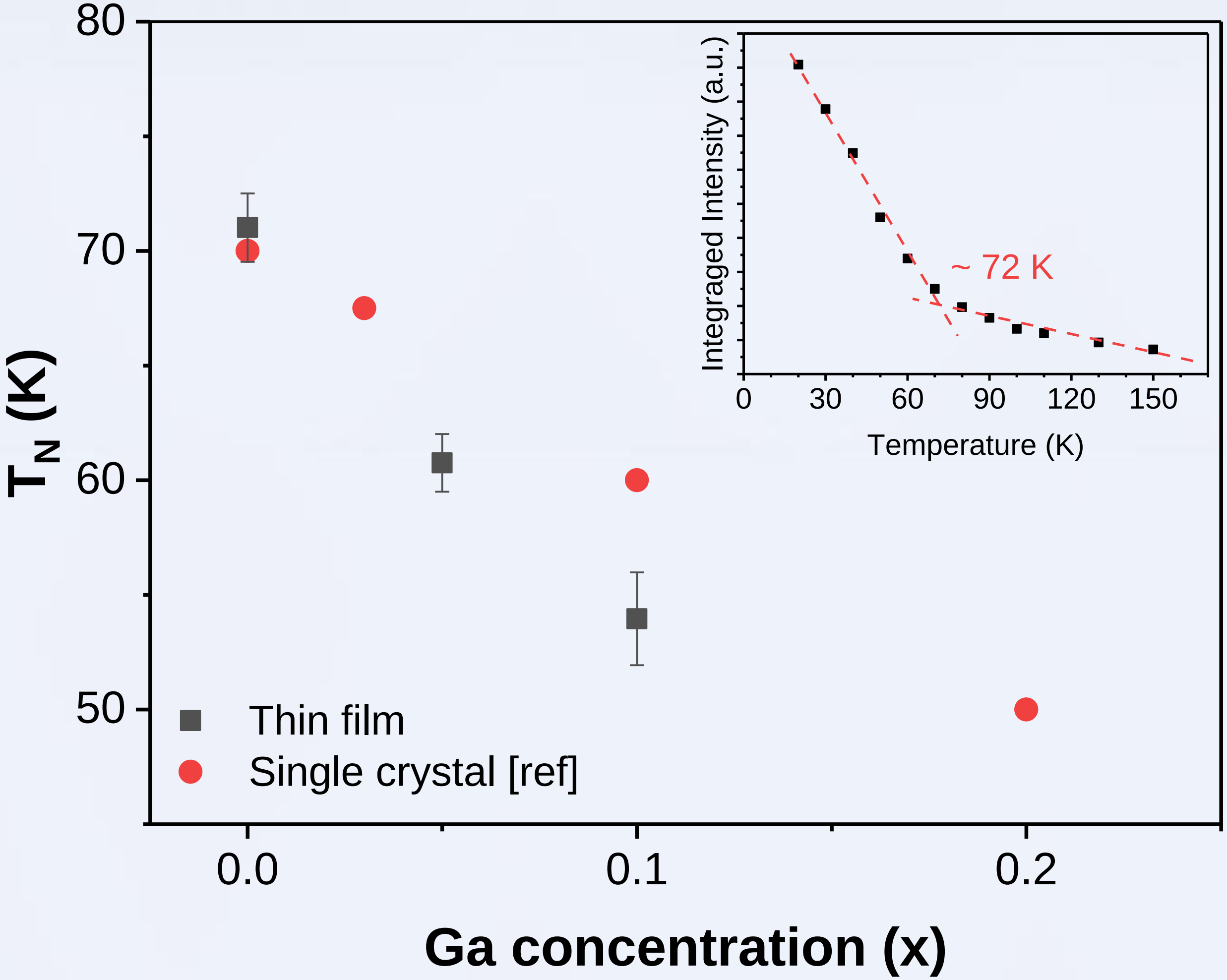
Analysis

1. Consider 60 × 60 Mn ion lattices. (X)
2. Give each ion a number from 1 to 3600.
3. Choose 5%, 10%, and 33% random numbers.
4. Assume that the Ga ions enter a position corresponding to a random number.
5. Remove Mn ions “affected” by Ga ions.-Previous page
6. Count the number of remaining Mn ions. (Y)
7. Get the ratio Y/X.

Analysis

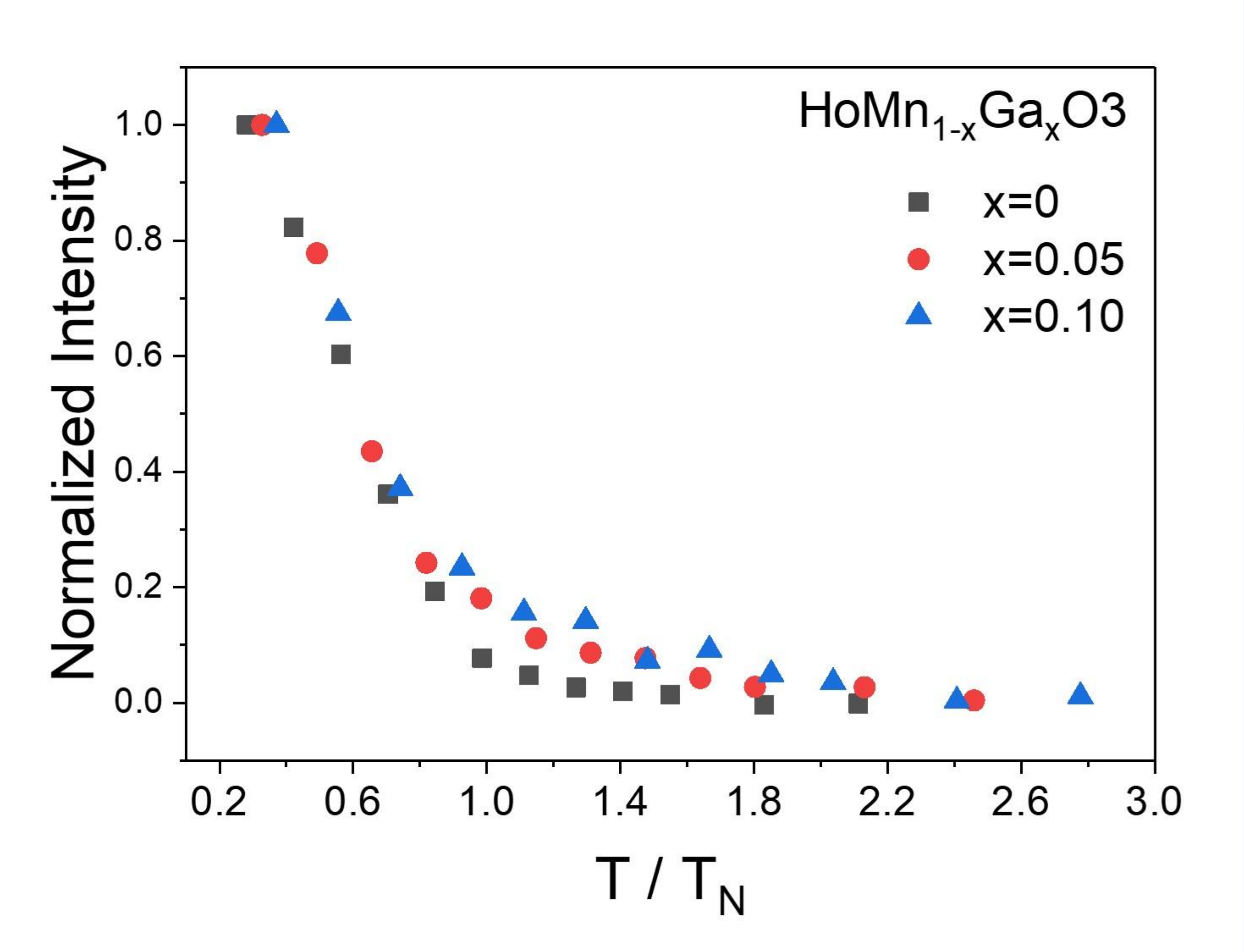


Relative Intensity
Ga concentration (%)
1.2
0.8
0.4
0.0
0.0
0.1
0.2
0.3
0.4
1 layer
2 layers
760 mode



80
70
60
50
T_N (K)
0.0
0.1
0.2
Ga concentration (x)
Thin film
Single crystal [ref]
Integraged Intensity (a.u.)
~ 72 K
0
30
60
90
120
150
Temperature (K)

Results



HoMn1-xGaxO3
x=0
x=0.05
x=0.10
Normalized Intensity
1.0
0.8
0.6
0.4
0.2
0.0
0.2
0.6
1.0
1.4
1.8
2.2
2.6
3.0
T / TN

Universal curve !

-> Spin excitation mechanism is not influenced by the Ga-substitution.

Substituting Ga ions affect the neighboring Mn ions only.

The spin excitations are limited in the Mn triangular network.

Summary:

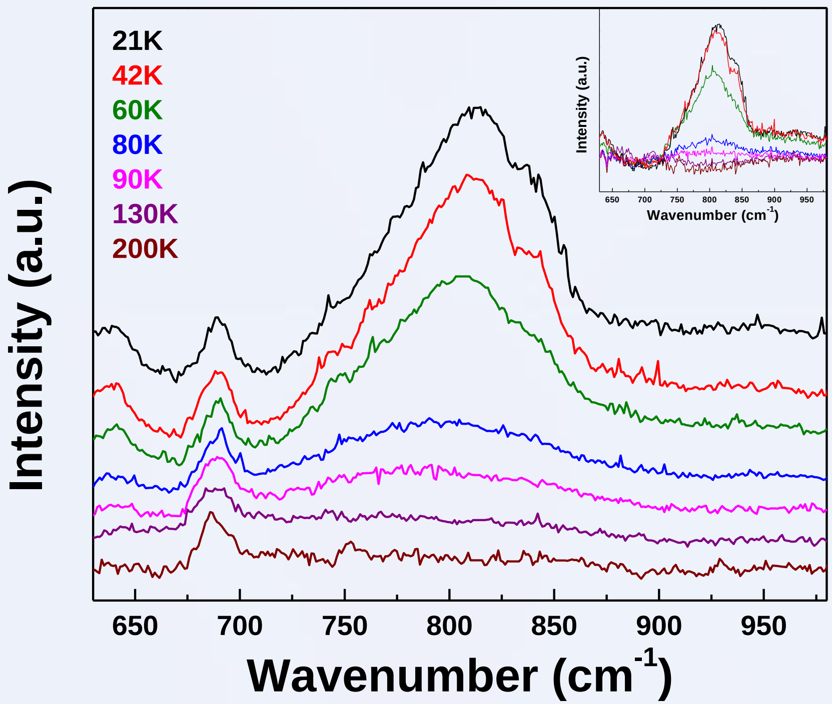
- We presented magnon scattering studies in $HoMn_{1-x}Ga_xO_3$ (x = 0, 0.05, 0.10 and 0.33) thin films.
- The spin-wave intensity has strong decrease by Ga substitution.
- We suggest a model of how Ga-ion substitution affects neighboring Mn ions.
- The effect of Ga-ion substitution is limited to the nearest Mn ions.
- The spin excitations seem to be localized in the Mn triangular network.

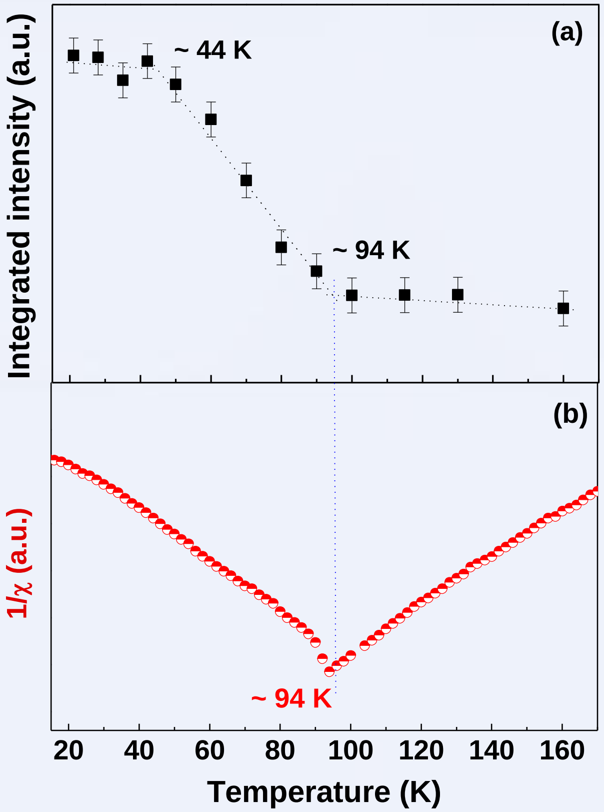
4. Raman study of magnetic phase transitions of hexagonal manganites single crystal $LuMnO_3$

5. "Spin wave and spin flip in hexagonal $LuMnO_3$ single crystal",
Xiang-Bai Chen, Peng-Cheng Guo, Nguyen Thi Huyen, Seung Kim,
In-Sang Yang, Xueyun Wang, Sang-Wook Cheong,
Appl. Phys. Lett. **110**, 122405 (2017).

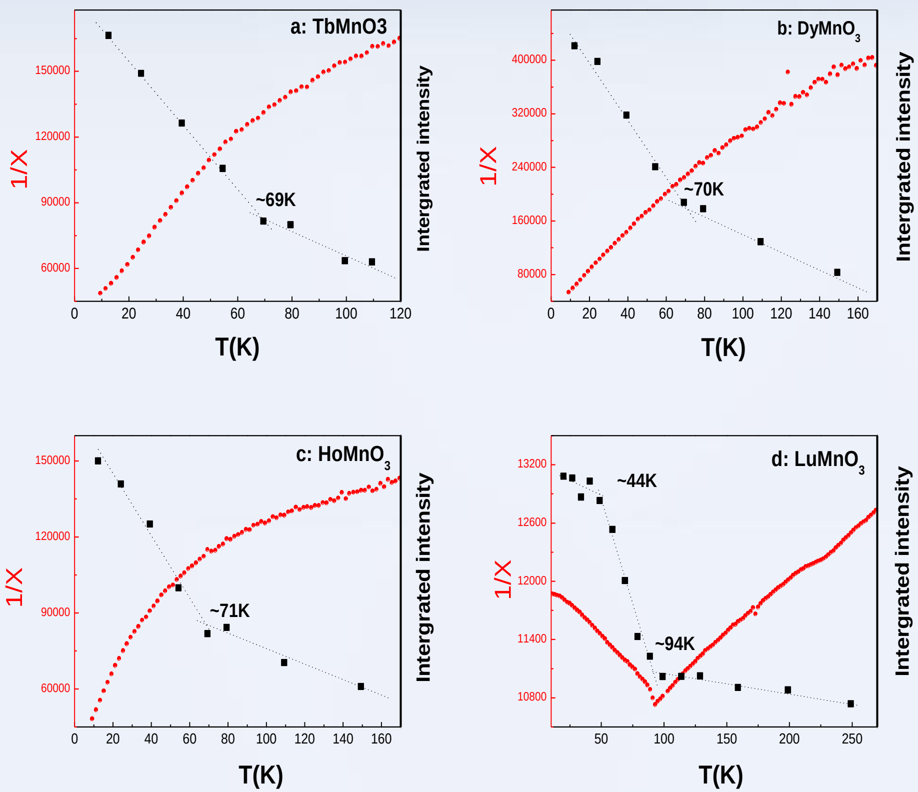
III. Raman results: *Spin excitation peaks*

T dependent (20K – 200K) Raman spectra of hexagonal $LuMnO_3$ single crystal in the cross configuration

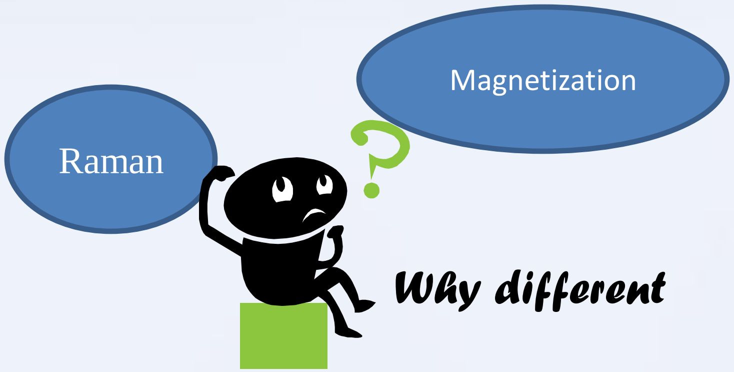




Raman vs. magnetization experiment of hexagonal $RMnO_3$



Thin films: *R*=Tb, Dy, Ho
Single crystal: *R*= Lu



Raman: probes the magnons in Mn^{3+} sublattices. Measure the skin-depth of the thin film, thus, it investigate the intrinsic properties of the thin film.

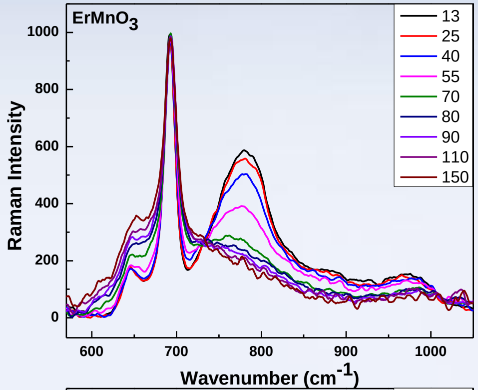
Magnetization: Strong paramagnetic contribution from the f-electron of the rare-earths dominate the magnetization data.
Substrate also measured at the same time.

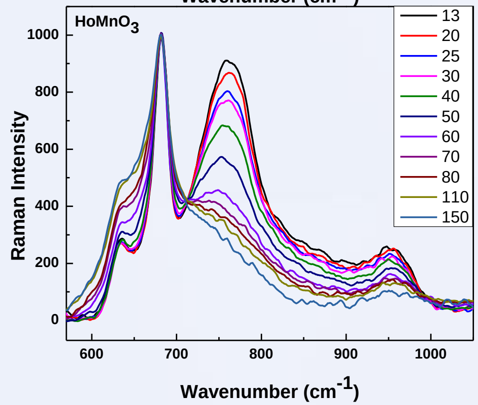
Magnon Raman spectra selectively probes magnons in the Mn^{+3} sublattices.
-> Effective to study the magnetic phase transitions due to Mn-spin ordering.

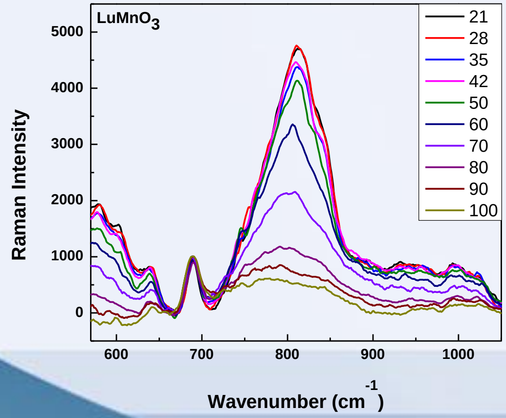
5. Two-Dimensional Correlation Analysis and Principal Component Analysis

6. Correlation between magnon and magnetic symmetries of hexagonal *R*MnO_3 (*R* = Er, Ho, Lu), Thi Minh Hien Nguyen, Thi Huyen Nguyen, Xiang-Bai Chen, Yeonju Park, Young Mee Jung, D. Lee, T.W. Noh, Sang-Wook Cheong, and In-Sang Yang, Journal of Molecular Structure 1124, 103-109 (2016).

II. *2D COS & PCA*







PRETREATMENT OF DATA

Normalize the reference peak at ~680cm^{-1} to 1000cts

Noise reduction: Savitzky- Golay smoothing method (13 points)

PCA

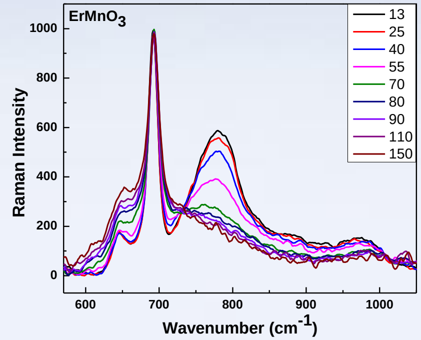
The PCA was performed using the PLS Toolbox ver. 7.3 (Eigenvector Research, Inc.) for Matlab (The MathWorks Inc.)

2D COS

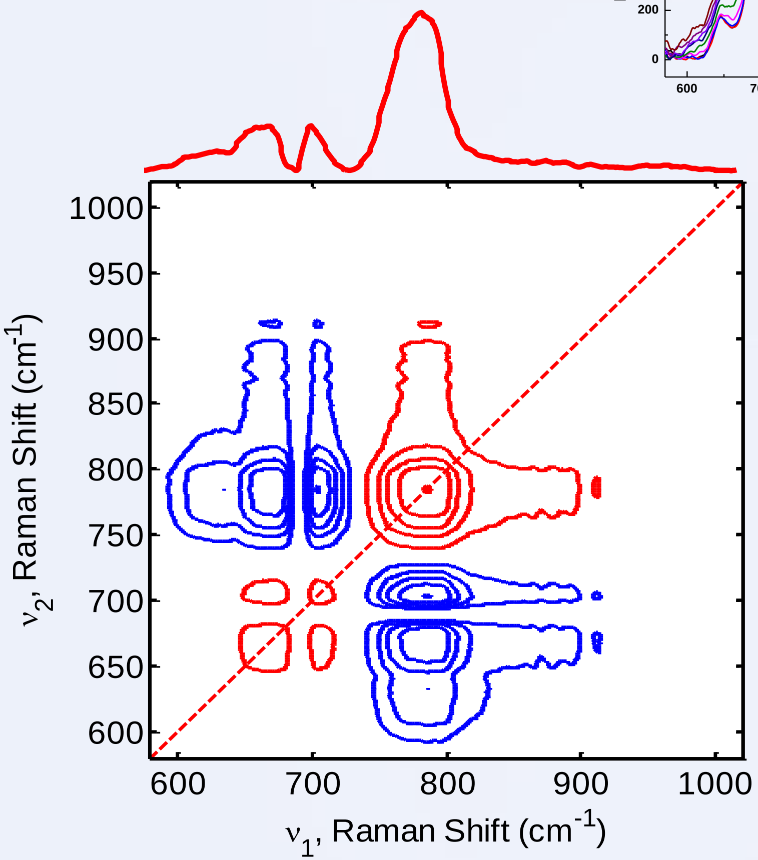
The 2D correlation spectra were obtained in Matlab R2013b

IV. Support from 2D COS & PCA: *$ErMnO_3$*

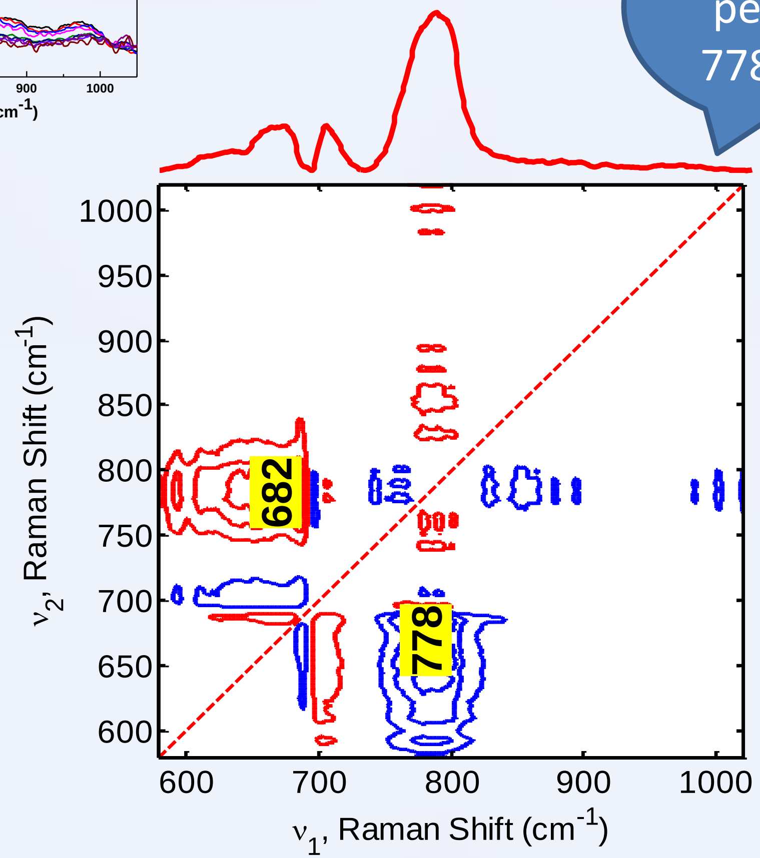
$ErMnO_3$



Only one peak at 778 cm^{-1}

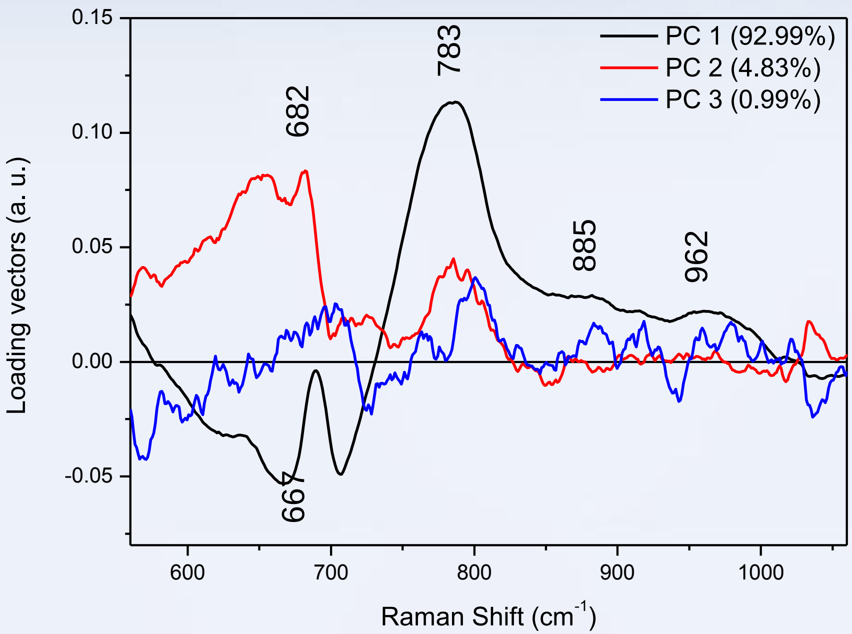


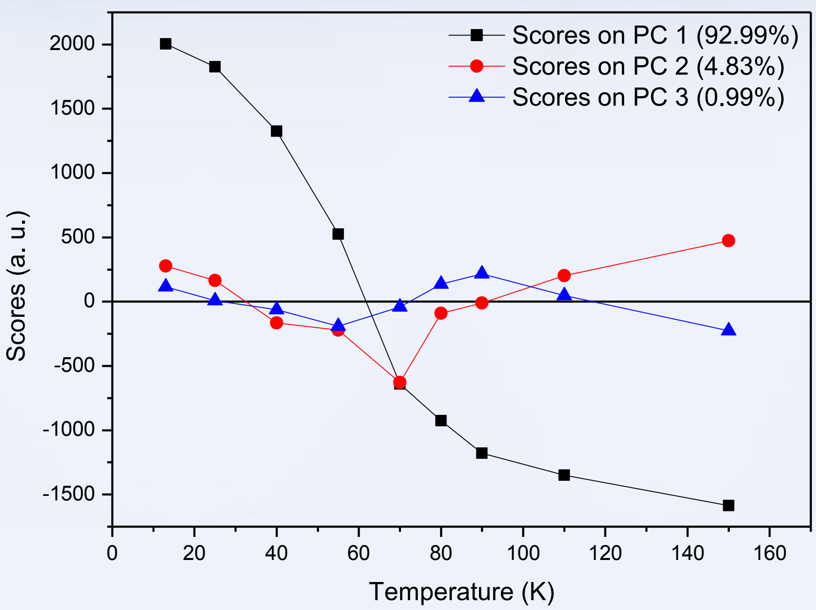
Synchronous



Asynchronous

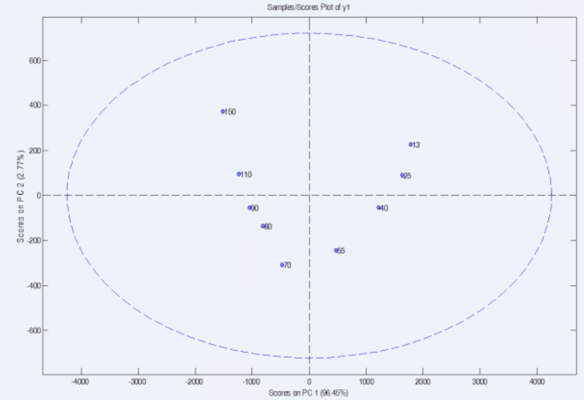
IV. Support from 2D COS & PCA: *$ErMnO_3$*



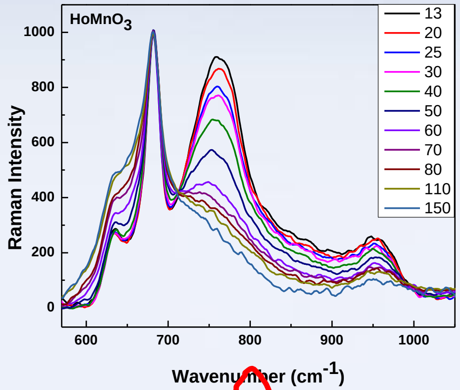


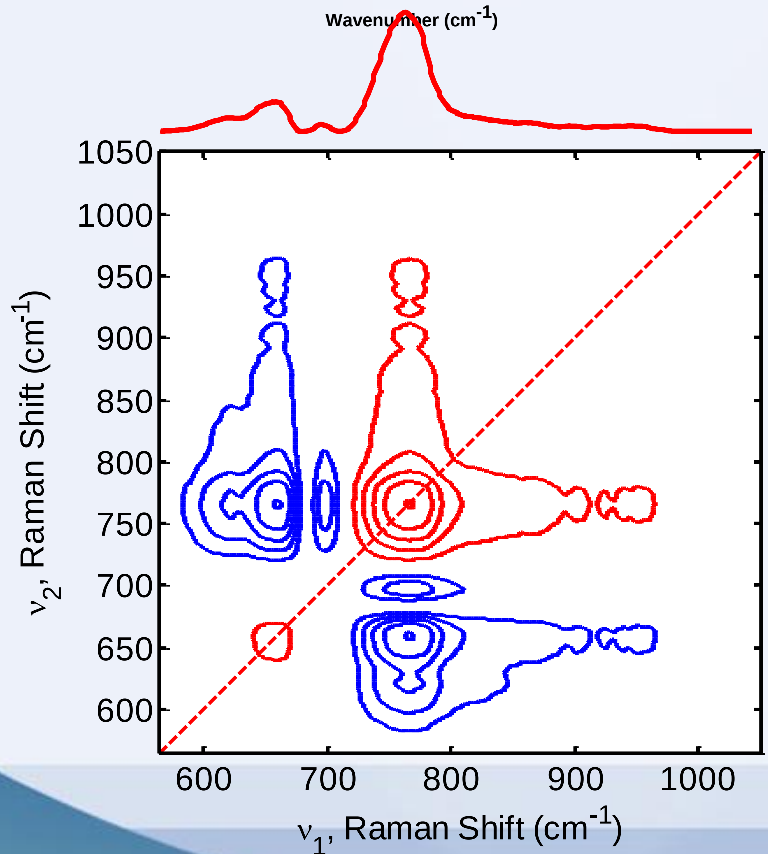
PC3: too noisy

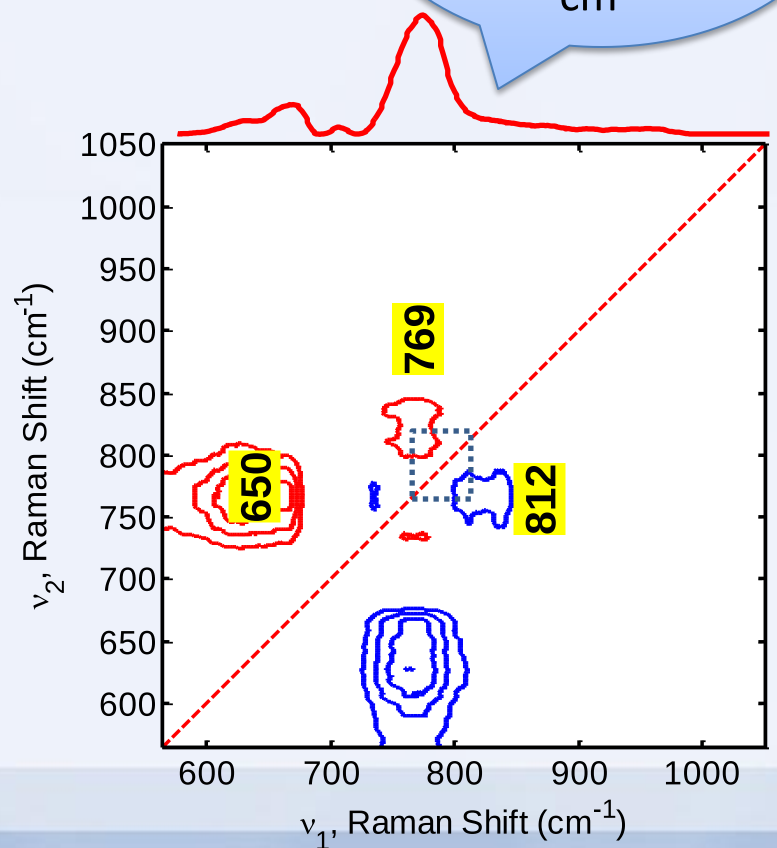
From PC1 & PC2: Broad magnon band of $ErMnO_3$ at ~778cm^{-1} consists of a single peak



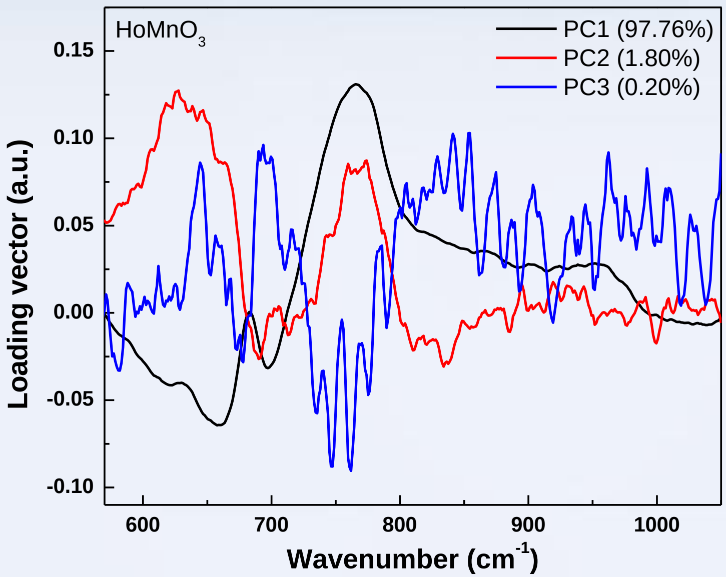
IV. Support from 2D COS & PCA: *$HoMnO_3$*

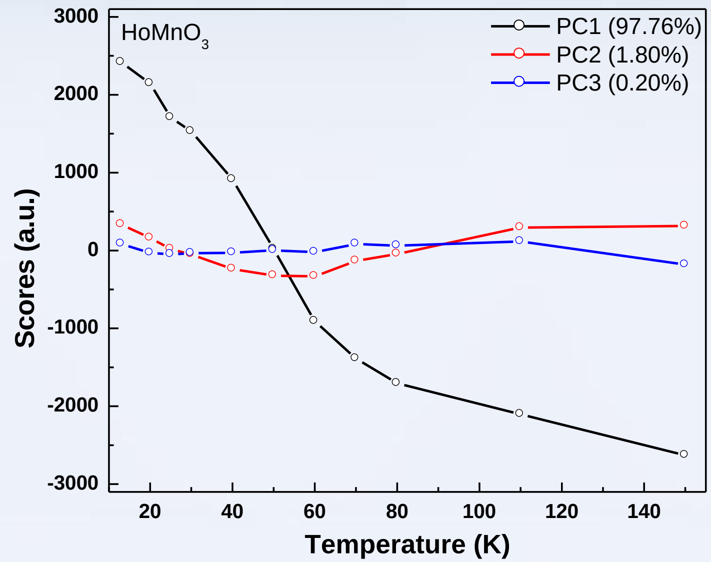






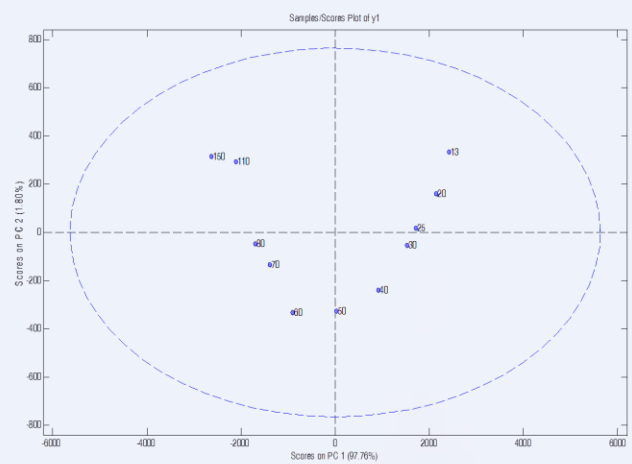
IV. Support from 2D COS & PCA: *$HoMnO_3$*



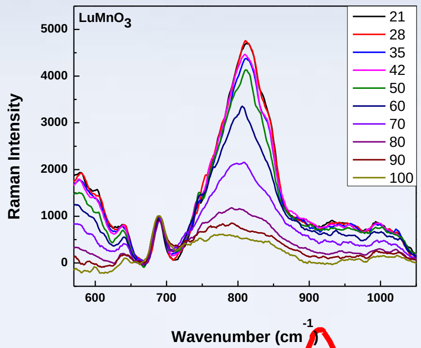


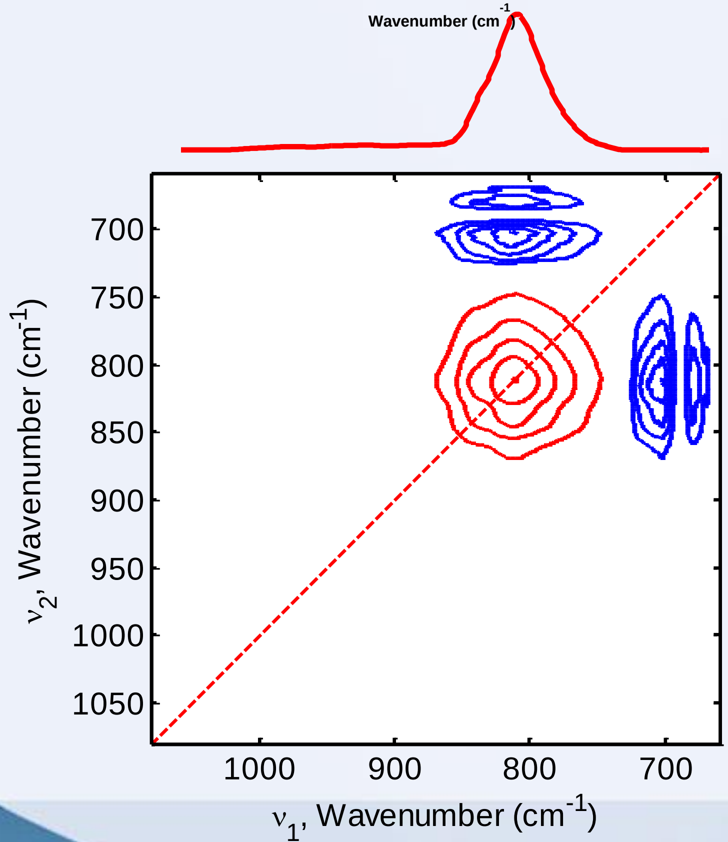
PC3: too noisy

From PC1 & PC2: Difficult to realize the broad band of $HoMnO_3$ at ~760cm^{-1} consists of 1 or 2 overlap peaks

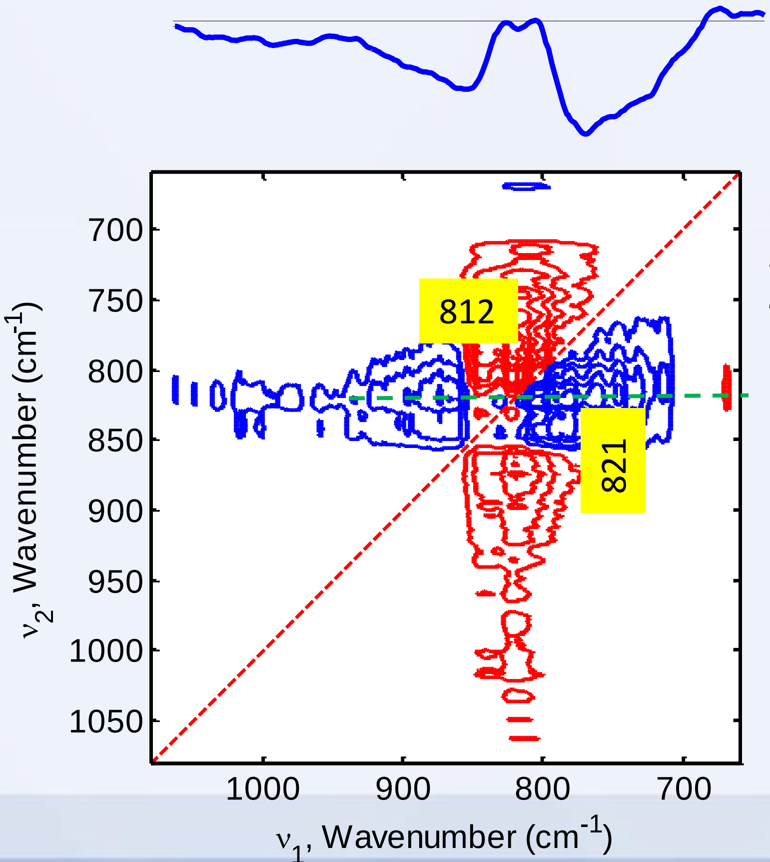


IV. Support from 2D COS & PCA: *$LuMnO_3$*



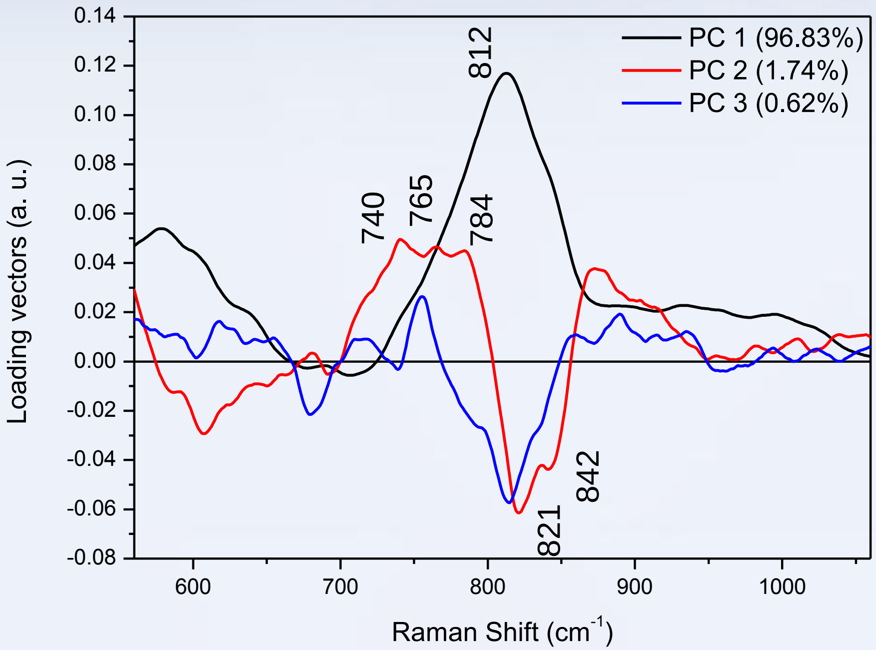


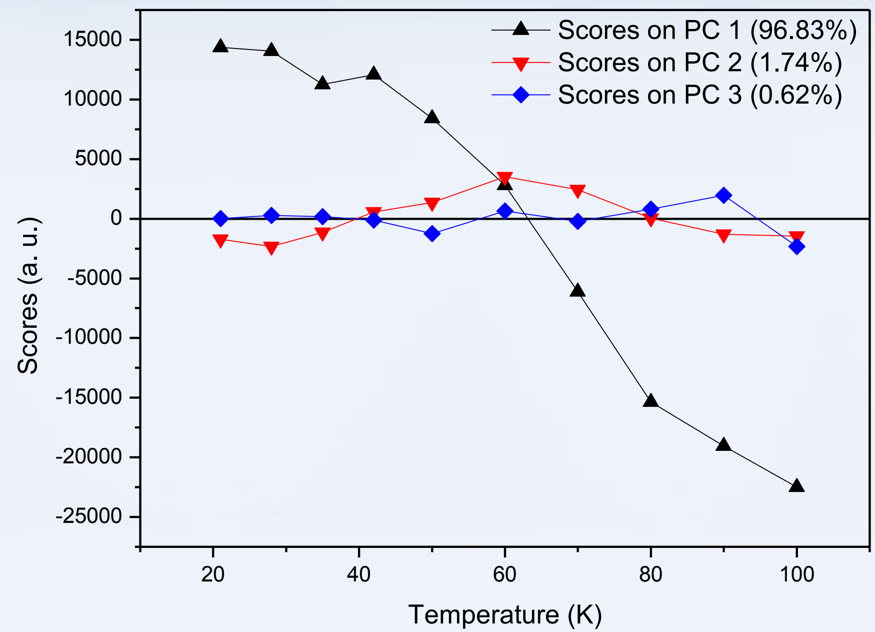
Asynchronous spectra is too noise, only realize 2 peaks at 812 & 821cm^{-1}



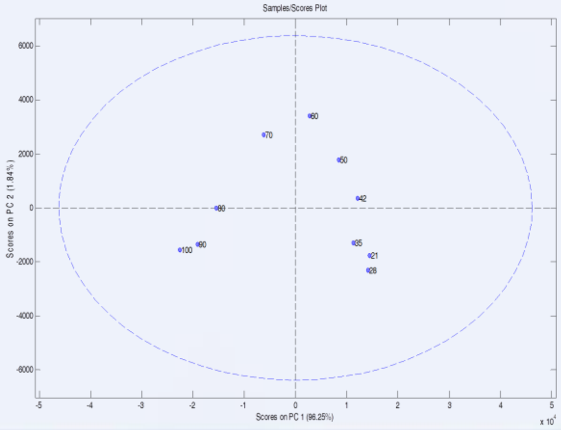
Slice cut at ~821cm^{-1}

IV. Support from 2D COS & PCA: *$LuMnO_3$*

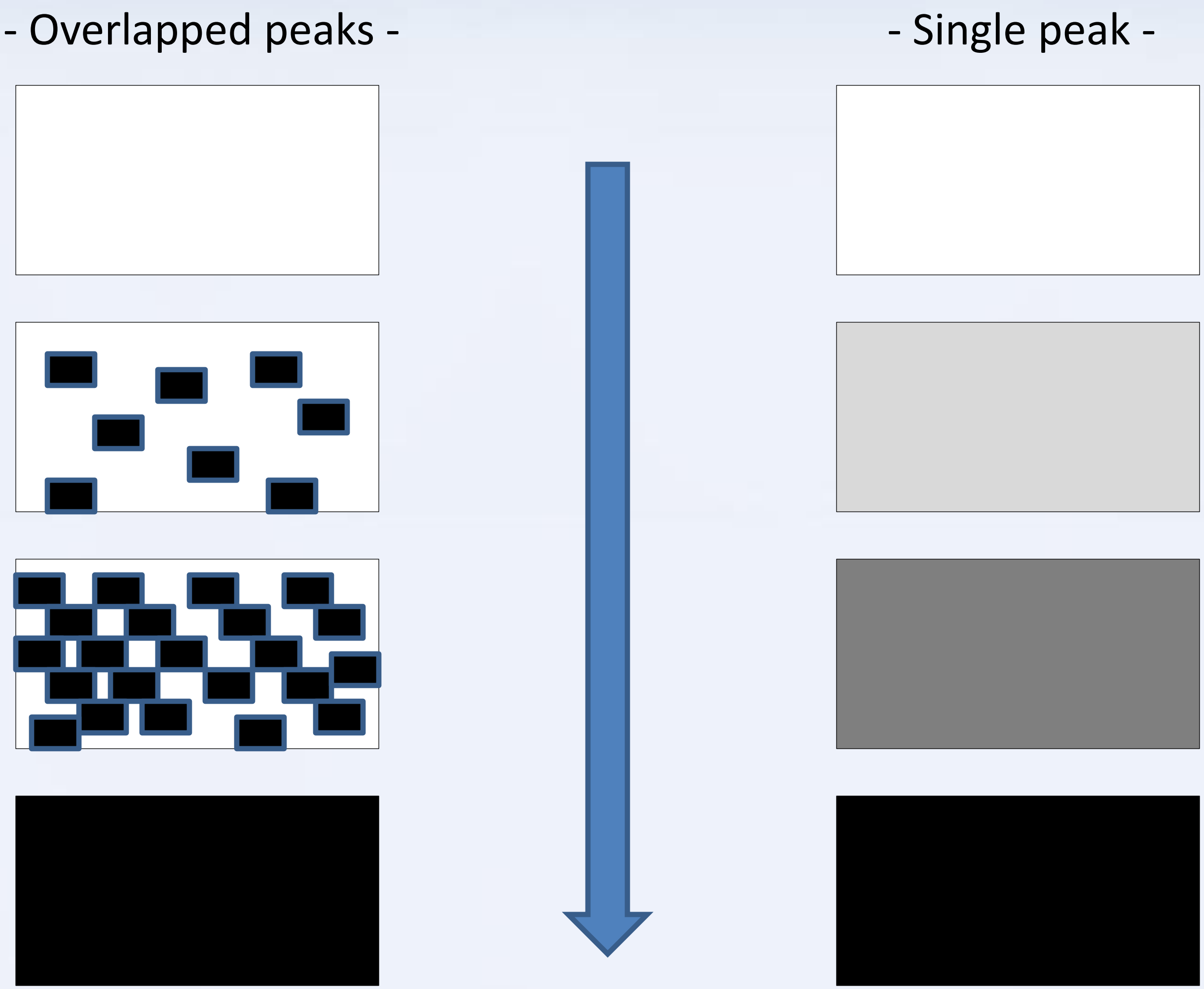




From PC1 and PC2: observed 6 peaks overlap in the broad magnon peak.

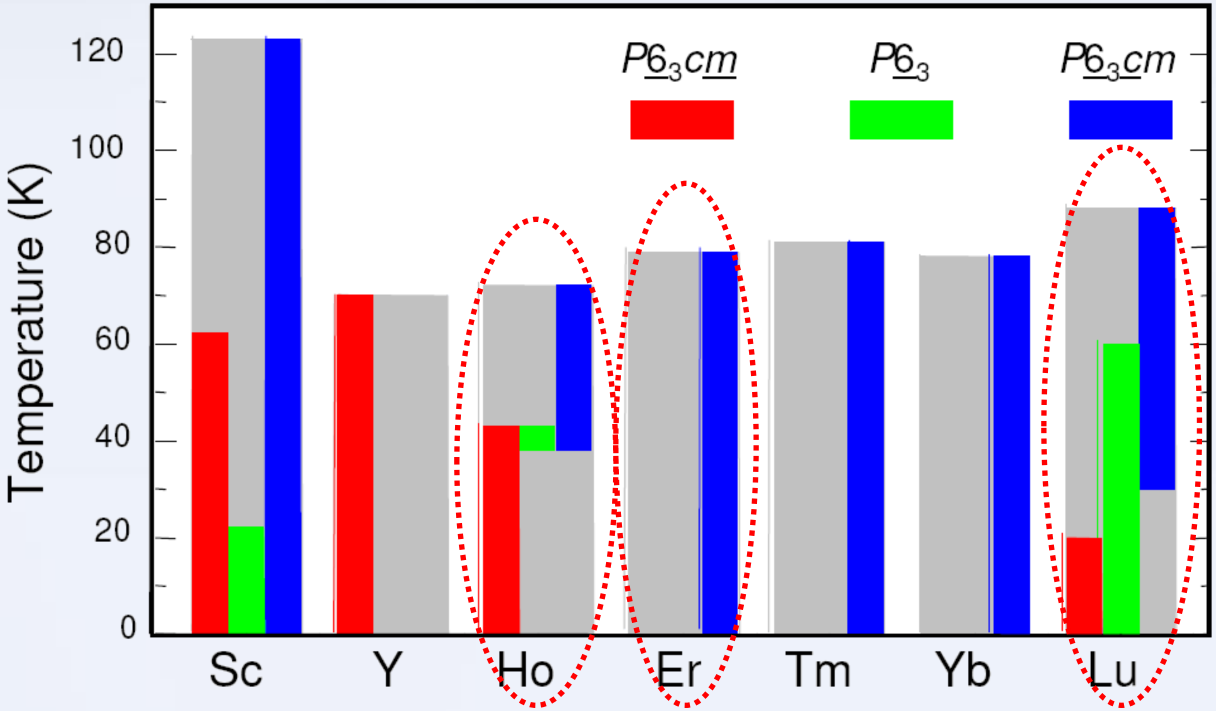


Overlap peaks vs Single peak



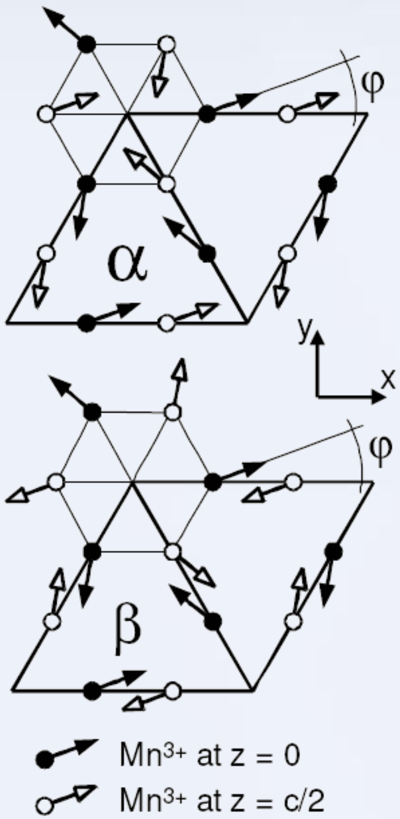
DISCUSSION

Symmetry of the hexagonal manganites $RMnO_3$



The symmetry of $LuMnO_3$ and $HoMnO_3$ are more complicated than that of $ErMnO_3$

$RMnO_3$: *Magnetic structure*



$T < T_C$:
ferroelectric

↓

Symmetry :
$P6_3cm$

$T < T_N$:
antiferromagnetic

↓

α_1 ($\varphi = 0°$):	***P*6₃c*m*** → $\mathbf{P\underline{6_3}c\underline{m}}$	β_1 ($\varphi = 0°$):	$\mathbf{P6_3\underline{cm}}$
$\chi_{yyy} = -\chi_{yxx} = -\chi_{xyx} = -\chi_{xxy}$		$\chi_{xyz} = \chi_{xzy} = -\chi_{yxz} = -\chi_{yzx}$	
α_2 ($\varphi = 90°$):	$\mathbf{P\underline{6_3c}m}$	β_2 ($\varphi = 90°$):	$\mathbf{P6_3cm}$
$\chi_{xxx} = -\chi_{xyy} = -\chi_{yxy} = -\chi_{yyx}$		$\chi_{zxx} = \chi_{zyy}$, $\chi_{xxz} = \chi_{xzx} = \chi_{yyz} = \chi_{yzy}$, χ_{zzz}	
α_φ ($0° < \varphi < 90°$):	$\mathbf{P\underline{6_3}}$	β_φ ($0° < \varphi < 90°$) :	$\mathbf{P6_3}$
$\chi(\alpha_1) \oplus \chi(\alpha_2)$		$\chi(\beta_1) \oplus \chi(\beta_2)$	

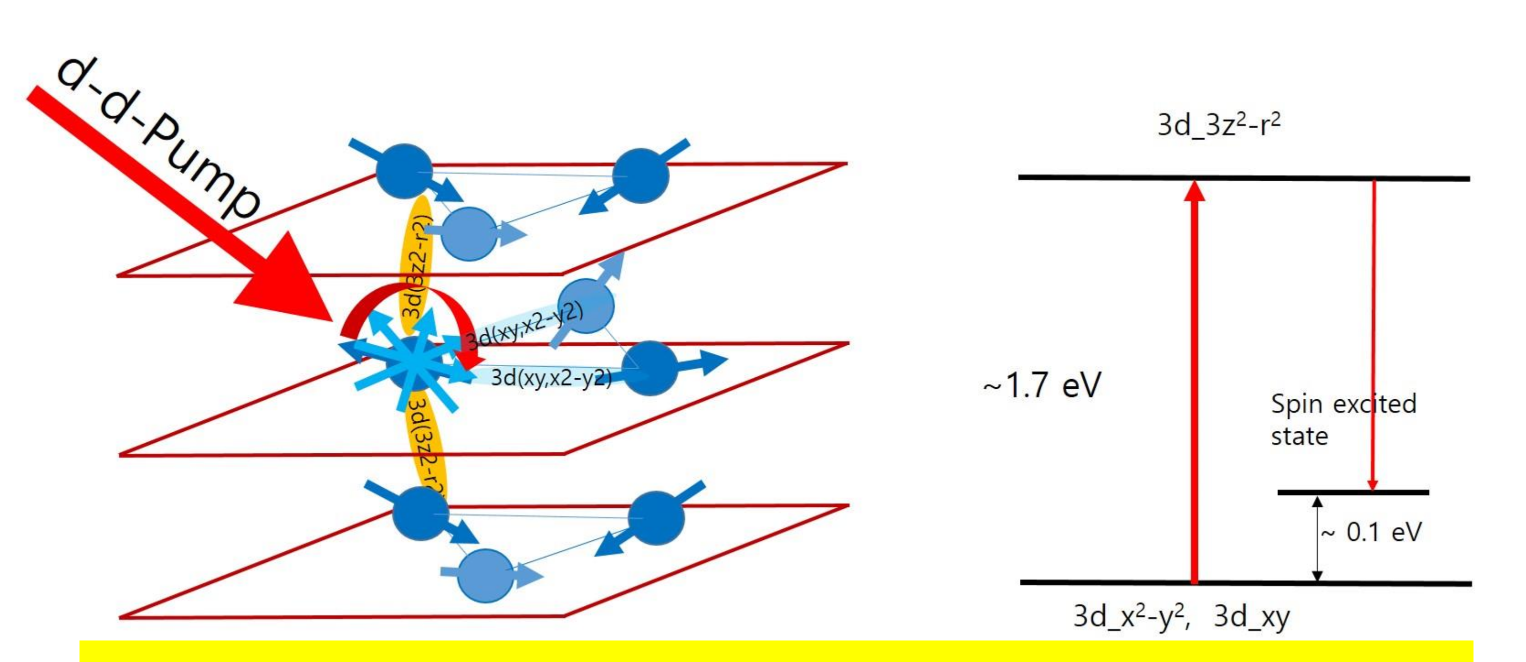
Summary:

- 2DCOS and PCA are performed on the temperature-dependent Raman spectra of hexagonal $RMnO_3$ (R=Ho, Er) thin films and $LuMnO_3$ single crystal.

- The difference in the magnon scattering of hexagonal $RMnO_3$ (R=Lu, Ho, Er) is correlated with the different magnetic symmetries of these materials.

Conclusion

- Spin excitations near 0.1 eV are found in hexagonal *R*MnO_3 by Raman spectroscopy.
- They are strongly resonant with 1.8 eV, near the Mn d-d transition.
- They correlate with the magnetic ordering of Mn^{3+} ions (T_N).



A scenario of spin-flip assisted by Mn d-d transition

THANK YOU FOR YOUR ATTENTION