

Tunable magnons of an antiferromagnetic Mott insulator via interfacial metal-insulator transitions

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This file contains all reviewer reports in order by version, followed by all author rebuttals in order by version.

Version 0:

Reviewer comments:

Reviewer #1

(Remarks to the Author)

This article focuses on utilizing RIXS to investigate magnon energy levels in AFM Mott Insulator, Sr_2IrO_4 with different substrates. The measurements show that magnon peak energy remains similar for $(\pi, 0)$ magnon mode. On the other hand, the measurements clearly show that softening of magnon mode occurs near $(\pi/2, \pi/2)$ zone boundary when metallic substrates are used. While, for insulating substrates the behavior is similar to bulk system. Although modifying the system from insulating to metallic causes hardening of the mode. In-plane exchange interactions are also extracted using Heisenberg spin model.

Electron-phonon coupling has been suggested as a potential reason for the dispersion, or magnon-phonon coupling driven by interface. However, no clear reason for the potential behavior or model is provided, including whether this behavior is expected to be universal or limited to the nature of interface or substrate? As such this study while notably characterizes the magnon modes in Sr_2IrO_4 , the overall impact on the field is not clear.

While these measurements are important and characterize critical behavior of magnon modes depending on substrate and boundary conditions which has so far been missing, and thus should be published. However, the advancement of underlying behavior in these systems is not clear, especially for Nature Communications.

Reviewer #2

(Remarks to the Author)

Sujan Shrestha and co-authors, in their work titled "Tunable Magnons of an Antiferromagnetic Mott Insulator via Interfacial Metal-Insulator Transition," presented detailed studies using resonant inelastic X-ray scattering and Raman spectroscopy on Sr_2IrO_4 heterostructures. They demonstrated that the properties of magnons in Sr_2IrO_4 films vary depending on their proximity to insulating or metallic substrates. Additionally, they showed that magnons are sensitive to the metal-insulator transition in $\text{Ca}_3\text{Ru}_{1.98}\text{Ti}_{0.02}\text{O}_7$ when used as the substrate.

The experimental data are very convincing, and the results merit publication. This work has the potential to advance a general understanding of magnons and offer direction to their applications. However, there are several issues that need to be addressed to strengthen the paper:

The explanation of the observed effects is somewhat speculative. I recommend providing a theoretical model to support the proposed ideas or offer the most plausible ones.

The TEM image in Figure S2 shows the interfacial region of the $\text{Sr}_2\text{IrO}_4/\text{Sr}_2\text{RuO}_4$ system. Since the paper's main results are particularly based on the $\text{Sr}_2\text{IrO}_4/\text{Ca}_3\text{Ru}_{1.98}\text{Ti}_{0.02}\text{O}_7$ system, including TEM data for this specific system as well as the sample $\text{Sr}_2\text{IrO}_4/\text{LSAT}$ will be vital to complete such study. Potential valence changes at interfaces are crucial in resolving magnetic and electronic properties. Therefore, investigating the atomic structure and valence state at the interface, possible charge transfer, and the interfacial diffusion (if so) of elements from the substrates is necessary for designing the model to explain the observed effects.

Minor Suggestions:

Please state the film thickness in both the main text and the supplementary information.

Reviewer #3

(Remarks to the Author)

The manuscript reports the experimental observation of softened zone boundary magnon energies in Sr₂IrO₄ heterostructures with metallic substrates compared with the films with insulating substrates. The authors present that the magnons can be tuned by growing the Sr₂IrO₄ on the substrate with a metal-insulator transition at 55K. They rule out the effect of strain, doping and proximity by various control experiments. The effect is attributed to electron-phonon coupling at the interface or within the substrate. However, the manuscript does not explain why and how the coupling softening the magnon energies at the zone boundary, thus difficult to access the fundamental insights. Also, the tunability is small, compared to another related work [Nature Communications 13, 6674 (2022)], in which the energies of zone-center magnons in Sr₂IrO₄ can be tuned by 40% with 0.1% stress. A theory part with quantitative explanation is needed, too. Therefore, I regret to say that I do not recommend for the publication of the manuscript in nature communications. The following are more detailed comments.

-The authors claimed that electron-phonon coupling at the interface or in the substrate might cause the magnon softening effect. But they do not explain why and how. Is it possible for the authors come up with a model to support their claim?

-Why the magnon softening effect happens only at the zone boundary, not other areas? Still a theory model or calculation is needed.

-How the temperature affect the magnon energies of single crystal Sr₂IrO₄? The authors claim the magnon tunability via interfacial metal-insulator transition. They do show the 40K and 60K magnon energy difference of Sr₂IrO₄ / Ca₃Ru_{1.98}Ti_{0.02}O₇. However, the temperature difference of magnon energies for the other samples are not given.

-In the first paragraph of the experimental layout part, the authors state "...the in-plane lattice of Sr₂IrO₄ thin films is coherently strained with all three substrates...". Generally when people talk about coherent they refer to a wave. What "coherently strained" means here?

-In the fourth paragraph of the result part, the authors state "A similar upward shift of up to 0.7 meV in the phonon energy is also observed in Sr₂IrO₄/Ca₃Ru_{1.98}Ti_{0.02}O₇ heterostructures when transitioning from an insulating to metallic state of the Ca₃Ru_{1.98}Ti_{0.02}O₇ substrate at 55 K (Fig. 5b)." It seems that the 0.7 meV energy is not the result by comparing two temperatures near the transition point (for example, 50K and 60K), but the value by comparing the highest energy 49.8meV at around 55K and lowest energy 49.1 meV at around 10K.

-In fig 5b, are the color bars are labeled wrong? The deep blue 52K energy jump to bright red 55K energy, then going back.

-How about A_{1g} mode of Sr₂IrO₄ / Ca₃Ru_{1.98}Ti_{0.02}O₇ in fig 5? The manuscript presents both A_{1g} and B_{2g} mode of Sr₂IrO₄/Sr₂RuO₄ and Sr₂IrO₄/LSAT in fig 5a. But only B_{2g} mode of Sr₂IrO₄ / Ca₃Ru_{1.98}Ti_{0.02}O₇ is presented fig 5b.

-In the fourth paragraph of the result part, the authors state "we acknowledge that the sudden structural change at 55 K might also have some contributions to the phonon mode shift in Sr₂IrO₄/Ca₃Ru_{1.98}Ti_{0.02}O₇ heterostructures". which one dominate the B_{2g} phonon Raman spectra shifting? The statement is too vague here.

-The year number is missing for the reference 20.

Version 1:

Reviewer comments:

Reviewer #1

(Remarks to the Author)

In the updated version, the authors have clearly highlighted the impact of these studies, the effect of heterostructure, and the lack of microscopic models, but have given possible mechanisms i.e. two magnon modes. According to me they have also addressed most referee comments, so I am okay with going forward with publishing the manuscript.

Reviewer #2

(Remarks to the Author)

The authors have addressed most of my comments/questions and those from other reviewers in a generally satisfactory manner. However, Reviewer #3 and I requested a more detailed explanation tailored to the studied heterostructure, which has not been provided. Some theoretical models must be an integral component of such a study.

To summarize, the paper presents some interesting experimental evidence that merits publication but does not advance beyond established knowledge in the field.

Therefore, I cannot recommend this manuscript for publication in Nature Communications in its current form.

Reviewer #3

(Remarks to the Author)

I think the authors have addressed all the comments from the reviewers in revised manuscript. Therefore I recommend the work to be published in Nature Communications.

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Reply to the Reviewers' comments

We sincerely appreciate the Reviewers for their valuable comments and suggestions, which help us improve the manuscript. Here, we reply to the comments in detail below:

Reviewer #1

The Reviewer said: *This article focuses on utilizing RIXS to investigate magnon energy levels in AFM Mott Insulator, Sr_2IrO_4 with different substrates. The measurements show that magnon peak energy remains similar for $(\pi,0)$ magnon mode. On the other hand, the measurements clearly show that softening of magnon mode occurs near $(\pi/2, \pi/2)$ zone boundary when metallic substrates are used. While, for insulating substrates the behavior is similar to bulk system. Although modifying the system from insulating to metallic causes hardening of the mode. In-plane exchange interactions are also extracted using Heisenberg spin model. Electron-phonon coupling has been suggested as a potential reason for the dispersion, or magnon-phonon coupling driven by interface. However, no clear reason for the potential behavior or model is provided, including whether this behavior is expected to be universal or limited to the nature of interface or substrate? As such this study, while notably characterizes the magnon modes in iridates, the overall impact on the field is not clear.*

While these measurements are important and characterize critical behavior of magnon modes depending on substrate and boundary conditions which has so far been missing, and thus should be published. However, the advancement of underlying behavior in these systems is not clear, especially for Nature Communications.

Our reply: We sincerely thank the reviewer for their insightful feedback and for recognizing the importance of our findings on the critical behavior of magnon modes in Sr_2IrO_4 , depending on the nature of the substrate. We also appreciate the reviewer's support for publishing our manuscript.

We agree with the reviewer that providing a deeper explanation of the underlying mechanisms for the observed magnon behavior is essential. Although our study focuses on iridate/ruthenate heterostructures, we believe that the observed substrate-dependent magnon dynamics could indeed

be a universal phenomenon, extendable to other systems. To support this claim, we have included additional references in our revised manuscript, noting private discussions with experts in the broader magnetic materials community, who have observed substrate-dependent magnon dynamics in other 2D magnetic materials, such as Fe_3GeTe_2 , NiPS_3 , and CrSBr , where the metallic or insulating nature of the substrate plays a significant role in determining the magnetic excitations. In such 2D materials, the experimental limitations of RIXS currently hinder a detailed study of full magnon dispersion, but preliminary observations suggest similar trends to those we report. We believe that this universality—magnon behavior influenced by hetero-interfaces in systems ranging from antiferromagnetic insulators to 2D magnets—highlights the broad relevance and impact of our findings.

Regarding the softening of the magnon mode near the $(\pi/2, \pi/2)$ zone boundary when a metallic substrate is used, we have expanded our discussion in the revised manuscript to provide more clarity on the possible mechanisms. We propose that this behavior is likely driven by electron-phonon coupling at the interface or within the metallic substrate, which could mediate long-range interactions between acoustic phonons and magnons, affecting the magnon dispersion in Sr_2IrO_4 . This hypothesis is grounded in our robust experimental findings, which show a clear correlation between the substrate's metallic nature and the magnon mode softening.

However, as the reviewer rightly points out, a detailed microscopic model is still lacking. While we have outlined plausible interactions (such as metallic interface-driven magnon-acoustic phonon coupling), deriving a fully predictive model Hamiltonian for this system remains a significant theoretical challenge. We acknowledge this gap and have explicitly stated in the revised manuscript that further theoretical work is needed to construct such a model. We believe that publishing our results will provide a strong experimental basis for future theoretical efforts, encouraging the development of more detailed models that can describe the complex interactions in heterostructures.

We strongly believe that our findings will significantly impact the field of magnonics. By demonstrating how substrate properties can be leveraged to manipulate magnon dispersion in an antiferromagnetic Mott insulator, we provide a novel approach to tuning magnetic excitations in layered materials. This tunability is crucial for the development of future magnonic devices, where

control over magnon dispersion could enable more efficient information processing and energy transport at the nanoscale. Our study opens up new avenues for exploring the effects of hetero-interfaces on magnetic excitations, not only in Sr_2IrO_4 but also in a wide range of magnetic materials, including 2D magnets and complex oxides.

We also believe that our manuscript provides a significant advancement in understanding substrate effects on magnon dynamics and will motivate both experimental and theoretical work in this exciting area. Publishing our work in *Nature Communications* will not only deepen the overall understanding of magnons but also stimulate research that explores new means of manipulating magnon energies in heterostructures, an essential step for advancing the field of magnonics.

Thank you.

Reviewer #2

The Reviewer said: *Sujan Shrestha and co-authors, in their work titled “Tunable Magnons of an Antiferromagnetic Mott Insulator via Interfacial Metal-Insulator Transition,” presented detailed studies using resonant inelastic X-ray scattering and Raman spectroscopy on Sr_2IrO_4 heterostructures. They demonstrated that the properties of magnons in Sr_2IrO_4 films vary depending on their proximity to insulating or metallic substrates. Additionally, they showed that magnons are sensitive to the metal-insulator transition in $\text{Ca}_3\text{Ru}_{1.98}\text{Ti}_{0.02}\text{O}_7$ when used as the substrate. The experimental data are very convincing, and the results merit publication. This work has the potential to advance a general understanding of magnons and offer direction to their applications.*

Our reply: We sincerely thank the reviewer for their positive feedback and support for publication! We are pleased to see that the strength of our experimental data and the potential of our findings to advance the understanding of magnons have been recognized.

Our study demonstrates how proximity to metallic or insulating substrates can effectively tune magnon properties in Sr_2IrO_4 , offering a new strategy for controlling magnon dynamics in complex oxide systems. This tunability is not only important for fundamental research but also has promising implications for the development of magnonic or spintronic devices, where precise control over magnetic excitations could enable novel applications in information processing and energy-efficient technologies.

We believe our work will inspire further research in this area. We appreciate the reviewer’s recognition of its broader impact.

The Reviewer said: *However, there are several issues that need to be addressed to strengthen the paper: The explanation of the observed effects is somewhat speculative. I recommend providing a theoretical model to support the proposed ideas or offer the most plausible ones.*

Our reply: We appreciate the reviewer’s suggestion. As mentioned in our response to Reviewer #1, we have expanded the discussion in the revised manuscript to offer more clarity. The most plausible explanation for the observed magnon softening is electron-phonon coupling at the

interface or within the metallic substrate, which could mediate long-range acoustic phonon-magnon interactions affecting magnon dispersion in Sr_2IrO_4 . This hypothesis is well-supported by our experimental data, showing a clear link between substrate metallicity and magnon behavior. However, developing a detailed microscopic theoretical model is extremely challenging and beyond the scope of this manuscript. While we outline plausible interactions such as magnon-acoustic phonon coupling, deriving a full theoretical model requires more information and ideas. We have acknowledged this gap and emphasized in the revised manuscript that further theoretical work is required. We believe our experimental results will provide a strong foundation for such efforts, encouraging the development of detailed models for magnon-acoustic phonon interactions in heterostructures.

The Reviewer said: *The TEM image in Figure S2 shows the interfacial region of the $\text{Sr}_2\text{IrO}_4/\text{Sr}_2\text{RuO}_4$ system. Since the paper's main results are particularly based on the $\text{Sr}_2\text{IrO}_4/\text{Ca}_3\text{Ru}_{1.98}\text{Ti}_{0.02}\text{O}_7$ system, including TEM data for this specific system as well as the sample $\text{Sr}_2\text{IrO}_4/\text{LSAT}$ will be vital to complete such study potential valence changes at interfaces are crucial in resolving magnetic and electronic properties. Therefore, investigating the atomic structure and valence state at the interface, possible charge transfer, and the interfacial diffusion (if so) of elements from the substrates is necessary for designing the model to explain the observed effects.*

Our reply: We thank the reviewer for this insightful suggestion. In response, we have added Figure S3 to the revised manuscript, which includes high-resolution TEM data of a $\text{Sr}_2\text{IrO}_4/\text{Ca}_3\text{Ru}_2\text{O}_7$ heterostructure. The data show a sharp interface along both the a and b directions with minimal ionic interdiffusion, suggesting that the heterostructure maintains its integrity.

For TEM purposes, $\text{Ca}_3\text{Ru}_2\text{O}_7$ with and without 1% Ti doping is structurally nearly identical. Given the challenges of growing large enough single crystals for heterostructure fabrication, obtaining TEM data from such samples is already a significant achievement. While cross-sectional TEM is sample-destructive and could potentially affect heterostructure integrity, it is reassuring that our data reveal a well-defined interface.

We also agree with the reviewer on the importance of further investigating the atomic structure, valence state, and potential charge transfer at the interface. For future studies, we plan to employ advanced techniques such as electron energy loss spectroscopy (EELS) to explore these aspects in greater detail.

The Reviewer said: *Please state the film thickness in both the main text and the supplementary information.*

Our reply: We have included the film thickness in both the main text and the supplementary information in the revised manuscript.

Thank you.

Reviewer #3

The Reviewer said: *The manuscript reports the experimental observation of softened zone boundary magnon energies in Sr_2IrO_4 heterostructures with metallic substrates compared with the films with insulating substrates. The authors present that the magnons can be tuned by growing the Sr_2IrO_4 on the substrate with a metal-insulator transition at 55 K. They rule out the effect of strain, doping and proximity by various control experiments. The effect is attributed to electron-phonon coupling at the interface or within the substrate. However, the manuscript does not explain why and how the coupling softening the magnon energies at the zone boundary, thus difficult to access the fundamental insights. Also, the tunability is small, compared to another related work [Nature Communications 13, 6674 (2022)], in which the energies of zone-center magnons in Sr_2IrO_4 can be tuned by 40% with 0.1% stress.*

Our reply: In [Nature Communications 13, 6674 (2022)], the energies of the zone-center magnons in a Sr_2IrO_4 single crystal were tuned by 40% with just 0.1% stress using a strain device. However, this tunability primarily targets the zone center, which has a very low energy of around 2.3 meV, meaning even a small energy shift results in a large percentage change. When we consider the magnitude of the shift in the zone-center magnon energy, it amounts to only about 0.7 meV for 0.1% stress. This absolute value is much smaller than the 20 meV shift observed at the zone boundary magnon energy in our study. Hence, the tunability of “magnon dispersion” is not so small when a Sr_2IrO_4 thin film is interfaced with different substrates.

The Reviewer said: *A theory part with quantitative explanation is needed, too. Therefore, I regret to say that I do not recommend the publication of the manuscript in nature communications. The authors claimed that electron-phonon coupling at the interface or in the substrate might cause the magnon softening effect. But they do not explain why and how. Is it possible for the authors come up with a model to support their claim?*

Our reply: We thank the reviewer for pointing out the importance of the theory part with the quantitative explanation. In the revised manuscript, we have attributed the softening of the magnon energy at the zone boundary in Sr_2IrO_4 interfaced with the metallic substrate to the combined

effects of electron-phonon and magnon-acoustic phonon interactions, based on our experimental findings. However, to clarify the microscopic mechanisms behind this phenomenon and to understand why and how it occurs, the model Hamiltonian is yet to be established for the heterostructures. We believe our experimental results will pave the way for a deeper understanding and manipulation of magnons, encouraging theorists to derive or identify the suitable Hamiltonian for this system.

The Reviewer said: *Why the magnon softening effect happens only at the zone boundary, not other areas? Still a theory model or calculation is needed.*

Our reply: Please note that our experimental finding is in changes of “magnon dispersion”, which is large enough to be observed in our experiments, RIXS and Raman spectroscopy. Thus, the magnon softening effect happening at the zone boundary implies an overall tuning of magnon dispersion. In the revised manuscript, we added relevant discussions: Changes in the second-nearest and third-nearest exchange interactions (J_2 and J_3) might be responsible for the tuning of magnon dispersion, supported by linear spin-wave theory and spin-Hamiltonian model fit. In particular, the spin-Hamiltonian fit provides quantitative information. We also believe that publishing our manuscript in Nature Communications will motivate theorists to derive or identify more advanced model Hamiltonians and calculations for this system.

The Reviewer said: *How the temperature affect the magnon energies of single crystal Sr₂IrO₄? The authors claim the magnon tunability via interfacial metal-insulator transition. They do show the 40K and 60K magnon energy difference of Sr₂IrO₄ / Ca₃Ru_{1.98}Ti_{0.02}O₇. However, the temperature difference of magnon energies for the other samples are not given.*

Our reply: According to [Phys. Rev. B **93**, 024405 (2016)], the single magnon energy at the zone center increases as the temperature decreases, with an energy change of only about 0.6 meV between 3 K and 140 K. This change in energy is very small compared to the 20 meV change in the zone boundary magnon energy. We selected 40 K and 60 K RIXS measurements for Sr₂IrO₄/Ca₃Ru_{1.98}Ti_{0.02}O₇ because the Ca₃Ru_{1.98}Ti_{0.02}O₇ single crystal substrate undergoes a metal-insulator transition at 55 K. The data at 40 K corresponds to the insulating state of the substrate, while the data at 60 K corresponds to its metallic state. Our RIXS measurements at the ($\pi/2$, $\pi/2$)

symmetry points, taken from 20 K to 60 K in 5 K intervals, clearly show a sudden shift of the single magnon energy to lower energy by 20 meV at 55 K, coinciding with the metallic state of $\text{Ca}_3\text{Ru}_{1.98}\text{Ti}_{0.02}\text{O}_7$. Thus, this shift is not simply a temperature effect but rather the result of the metal-insulator transition of the adjacent substrate.

In contrast, since there is no metal-insulator transition in Sr_2RuO_4 or LSAT single crystals below the Néel temperature of Sr_2IrO_4 , there is no necessity to perform RIXS measurements at different temperatures. Therefore, we conducted the RIXS measurements of $\text{Sr}_2\text{IrO}_4/\text{Sr}_2\text{RuO}_4$ and $\text{Sr}_2\text{IrO}_4/\text{LSAT}$ solely at 20 K.

The Reviewer said: *In the first paragraph of the experimental layout part, the authors state “...the in-plane lattice of Sr_2IrO_4 thin films is coherently strained with all three substrates...”. Generally when people talk about coherent they refer to a wave. What “coherently strained” means here?*

Our reply: In that paragraph, “coherently strained” means uniformly strained with the substrate without noticeable lattice relaxation. We have replaced the word “coherently” with “without relaxation” in the revised manuscript.

The Reviewer said: *In the fourth paragraph of the result part, the authors state “A similar upward shift of up to 0.7 meV in the phonon energy is also observed in $\text{Sr}_2\text{IrO}_4/\text{Ca}_3\text{Ru}_{1.98}\text{Ti}_{0.02}\text{O}_7$ heterostructures when transitioning from an insulating to metallic state of the $\text{Ca}_3\text{Ru}_{1.98}\text{Ti}_{0.02}\text{O}_7$ substrate at 55 K (Fig. 5b).” It seems that the 0.7 meV energy is not the result by comparing two temperatures near the transition point (for example, 50K and 60K), but the value by comparing the highest energy 49.8meV at around 55K and lowest energy 49.1 meV at around 10K.*

Our reply: Thank you so much to the reviewer for pointing out this question. According to [Appl. Phys. Lett. **114**, 152402 (2019)], the energy of the Raman shift in Sr_2IrO_4 single crystals decreases with increasing temperature. A similar trend is observed in $\text{Sr}_2\text{IrO}_4/\text{Ca}_3\text{Ru}_{1.98}\text{Ti}_{0.02}\text{O}_7$ above 55 K. However, below 55 K, the Raman shift energy increases with temperature, likely due to a sudden structural change occurring at this point. If this were merely a temperature effect and related to the metal-insulator transition, one would expect the Raman shift energy at 52 K to be lower than that

at 10 K. Thus, a comparison of 0.7 meV is made between the Raman shift energies at 10 K and 55 K.

The Reviewer said: *In fig 5b, are the color bars labeled wrong? The deep blue 52K energy jumps to bright red 55K energy, then going back.*

Our reply: Thank you to the reviewer for highlighting this issue. The color bar was correctly labeled, but it was inconsistent with Figure 4b. We have now adjusted the colors for each temperature in the updated manuscript to ensure consistency with Figure 4b and avoid any confusion.

The Reviewer said: *How about A_{1g} mode of Sr_2IrO_4 / $Ca_3Ru_{1.98}Ti_{0.02}O_7$ in fig 5? The manuscript presents both A_{1g} and B_{2g} mode of Sr_2IrO_4/Sr_2RuO_4 and $Sr_2IrO_4/LSAT$ in fig 5a. But only B_{2g} mode of Sr_2IrO_4 / $Ca_3Ru_{1.98}Ti_{0.02}O_7$ is presented fig 5b.*

Our reply: Thank you to the reviewer for raising this question. The reason we did not include the A_{1g} mode of $Sr_2IrO_4/Ca_3Ru_{1.98}Ti_{0.02}O_7$ is that the A_{1g} mode of Sr_2IrO_4 thin film overlaps with that of the $Ca_3Ru_{1.98}Ti_{0.02}O_7$ single crystal substrate, making it difficult to distinguish.

The Reviewer said: *In the fourth paragraph of the result part, the authors state “we acknowledge that the sudden structural change at 55 K might also have some contributions to the phonon mode shift in $Sr_2IrO_4/Ca_3Ru_{1.98}Ti_{0.02}O_7$ heterostructures”. Which one dominate the B_{2g} phonon Raman spectra shifting? The statement is too vague here.*

Our reply: Thank you so much to the reviewer for pointing out this question. In this statement, we acknowledge that both the structural change and the metal-insulator transition occur at 55 K, suggesting that the structural change may also contribute to the hardening of the phonon modes. However, we believe that the primary factor driving the shifting of the B_{2g} phonon mode is the metal-insulator transition of the adjacent substrate. This assertion is supported by the observation of softened zone boundary magnons and hardened phonon modes in the Sr_2IrO_4/Sr_2RuO_4 heterostructure, which has a metallic substrate, compared to the insulating substrate in

$\text{Sr}_2\text{IrO}_4/\text{LSAT}$. Similar behavior is observed in the $\text{Sr}_2\text{IrO}_4/\text{Ca}_3\text{Ru}_{1.98}\text{Ti}_{0.02}\text{O}_7$ heterostructure due to the metal-insulator transition of the $\text{Ca}_3\text{Ru}_{1.98}\text{Ti}_{0.02}\text{O}_7$ substrate.

The Reviewer said: *The year number is missing for the reference 20.*

Our reply: We have added the year to reference 20 in the updated manuscript.