nature portfolio

# Peer Review File

# Structural reconfiguration of interacting multi-particle systems through parametric pumping

Corresponding Author: Mr Qinghao Mao

**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 manuscript describes experimental studies of a protocol for organizing acoustically levitated rafts of granular matter into desired configurations. The method is inspired by optical pumping of atomic systems in which undesired stable states are driven into unstable excited states that then have some probability to relax into desired stable states. Pumping is achieved in the acoustic system by modulating the acoustic levitator's high-frequency drive with a low-frequency sine wave whose frequency and amplitude are chosen to destabilize all but the desired structure. The drive frequency, the modulation frequency and the modulation amplitude serve as control parameters for this acoustic pumping protocol. Optimal parameters are chosen based on a numerical evaluation of the interactions between pairs performed in COMSOL. The computed forces incorporate conservative wave-mediated interactions, nonconservative streaming forces and nonreciprocal wave-mediated interactions. Results of these computations are presented in Fig. 2e, Fig. 3d and Fig. 4a for increasingly complicated clusters of spheres. Experimental and numerical methods are described clearly in the Methods section.

The Supplementary information usefully explains the nitty gritty details of how modulating the drive signal actually modulates the pressure amplitude in the resonant cavity. This in turn explains the detailed shape of the state curves for different center frequencies in Figs. 2e, 3d and 4a. Additional information about the Markov selection sequences similarly helps to clarify the results in the main text. This is an appropriate use of Supplementary Information and helps to enhance the paper by moving detailed explanations out of the main text.

This study of dynamic acoustic trapping is timely, the work is original and the successful demonstration of structure selection in a complex driven system will excite a lot of interest. I recommend that this paper be published in Nature Communications.

I am particularly impressed by the demonstration in Fig. 3 of controlled switching between structures with five-fold and four-fold symmetry using nothing but the time dependence of the amplitude of a uniform plane standing wave. The demonstration in Fig. 5 that the size of large clusters can be controlled with parametric pumping creates opportunities for practical applications.

Although the text is generally clear, it still would benefit from careful editing. Two examples illustrate that the issues are minor but still worth fixing: Line 194: "... when starting from 10^4 initial ..." Line 64: "More details ... is discussed ..."

Reviewer #2

(Remarks to the Author)
Dear editors,

In this work, the authors establish parametric pumping as a method for the configurational control of acoustically levitated particle clusters.

By modulating the amplitude of an acoustic trap at the resonant frequency of a levitated cluster and subsequently turning off the modulation, structures are first rendered unstable and then allowed to reorganize. Since the pumping only affects undesired configurations, these are eventually selected out upon repeating the process leaving a preferred configuration.

The authors first demonstrate experimentally the principle with a two particle structure, then show controlled configuration switching in a five particle cluster and finally use pumping as a way to reduce cluster size by expelling particles from the acoustic trap. In simulation, scenario's with higher particle numbers are explored, demonstrating robustness of the approach.

The presented work nicely circumvents the hard problem of navigating between fixed points of an out-of-equilibrium energy landscape, by providing a selective mechanism to break up unwanted structures. While existing approaches to the assembly of e.g. colloidal structures rely on models of the energy landscape, the presented pumping strategy only requires a priori knowledge of the vibrational spectra of cluster configurations. This constitutes a promising step towards more robust self-assembly of particulate structures, where it has been difficult to gain control over which clusters to break up and which to keep. The text and figures are very clear and pedagogical.

For all these reasons, I consider it a good fit for Nature Communications.

However, I have some concerns regarding the generalization towards larger clusters and optical trapping:

· Fig 4d shows how the probability of not finding the icosahedral state falls off exponentially as a function of quench steps. Presumably this configuration was chosen for its increased stability due to symmetry. I wonder how the probability decay varies for the various other stable states: how many quench steps are needed for the least stable state to be reached?

· The presented strategy promises to generalize to other trapped settings such as in optics and fluidics and also to higher particle number. However, in those situations, it may not always be feasible to do FEM simulations in order to find the linear stiffness matrix, especially as the number of particles increases. How does this approach scale with larger cluster sizes? Could for instance a reduced order model of the trapped particles be used to find the stiffness matrix?

· In a similar vein, to what extent do the vibrational modes and growth rates depend upon the strength and nature of the nonreciprocal interactions? More

generally, what is the role of non-reciprocity in enabling the growth of the vibrational modes?

· In fig.5, the authors show how pumping can expel particles from the trap. I wonder if a more stronger or more nonlinear trap would instead create dynamical steady states such as limit cycles. Could the authors comment on the feasibility of creating dynamical steady states through pumping?

Minor comments:

· Line 37-38 should state that 'states […] are not isospectral, i.e. have distinguishable vibrational bands.'

· Line 89-90 mentions that the growth rate seen in the pumping state diagram of fig2e are similar to solutions to Mathieu's equation. It would be more precise perhaps to refer the pattern seen there as an Arnold tongue.

· Line 93: 'Only regions above them' is a bit vague, instead I recommend using gamma2*>1.

Reviewer #3

(Remarks to the Author)
I co-reviewed this manuscript with one of the reviewers who provided the listed reports. This is part of the Nature Communications initiative to facilitate training in peer review and to provide appropriate recognition for Early Career Researchers who co-review manuscripts.

Reviewer #4

(Remarks to the Author)
The paper explores parametric pumping via amplitude modulation in a single-transducer system for manipulating acoustically levitated multi-particle systems. It demonstrates transitions between stable and unstable configurations, highlighting emergent dynamics and non-reciprocal interactions. The simplified setup offers an accessible alternative to phased arrays while providing insights into modulation-driven behaviour.

This work examines near-field acoustic manipulations, where particle dynamics are governed by localized gradients near the sound source. This contrasts with far-field studies (e.g., Hirayama et al., 2019; Caleap & Drinkwater, 2014) that explore broader dynamics in spatially extended fields generated by phased arrays. While the near-field focus is a noteworthy contribution, it limits the generalizability of the findings, and explicitly addressing this distinction and its implications would enhance the paper.

The paper highlights non-reciprocal interactions as a novel feature, but this claim feels overstated, particularly in light of the authors' prior work (Lim et al., 2024), which demonstrates that non-reciprocity naturally arises in acoustically mediated systems through field-mediated interactions rather than direct particle-particle forces. This behavior is a well-known property of multi-particle acoustic systems in the Rayleigh regime, driven by the sound field's influence.

While non-reciprocity is an intriguing aspect of acoustic manipulation, the paper does not significantly expand on this established concept. To strengthen this aspect, the authors should provide a deeper theoretical analysis of how non-reciprocal dynamics influence particle transitions or explore broader implications and applications beyond what is already known.

The authors' prior work (Lim et al., 2024) offers a comprehensive framework for modeling acoustic interactions, including secondary forces, micro-streaming, and Rayleigh regime dynamics. The current paper largely reiterates these principles without substantial new contributions. Although this reference is briefly mentioned in the introduction, it is not meaningfully integrated into the main discussion. To clarify the novelty of the present study, the authors should engage more deeply with their prior work, highlighting how this paper builds upon or diverges from those earlier findings.

Overall, this work risks being seen as incremental in scope, given the exhaustive modeling the authors have already published in May 2024 (available on arXiv since January 2024). Addressing these concerns, particularly by clarifying the novelty and integrating prior work more effectively, would greatly improve the paper's impact. However, irrespective of these improvements, I do not believe this work meets the standard or broad significance required for publication in Nature Communications.

References
1. Hirayama, R., Martinez Plasencia, D., Masuda, N., et al. (2019). A volumetric display for visual, tactile, and audio presentation using acoustic trapping. Nature, 575(7783), 320–323. https://doi.org/10.1038/s41586-019-1739-5
2. Caleap, M., & Drinkwater, B. W. (2014). Acoustically trapped colloidal crystals that are reconfigurable in real time. Proceedings of the National Academy of Sciences, 111(47), 17179–17184. https://doi.org/10.1073/pnas.1417219111

Reviewer #5

(Remarks to the Author)
I co-reviewed this manuscript with one of the reviewers who provided the listed reports. This is part of the Nature Communications initiative to facilitate training in peer review and to provide appropriate recognition for Early Career Researchers who co-review manuscripts.

Version 1:

Reviewer comments:

Reviewer #2

(Remarks to the Author)
The authors have successfully addressed the comments of the reviewers. We therefore recommend publication of the manuscript in its present form.

Reviewer #3

(Remarks to the Author)
I co-reviewed this manuscript with one of the reviewers who provided the listed reports. This is part of the Nature Communications initiative to facilitate training in peer review and to provide appropriate recognition for Early Career Researchers who co-review manuscripts.

Reviewer #4

(Remarks to the Author)
I appreciate the authors' responses to my concerns. Upon reflection and after carefully considering their clarifications, I now recognize the novelty and significance of their work more.

Indeed, the approach of integrating near-field and far-field methods could be very powerful, enhancing the scalability and precision of particle assembly.

The authors' response to their prior work (Lim et al 2024) was also helpful. I appreciate that they are now moving from passive observation to active structural control. The dynamic switching of configurations using parametric pumping, as illustrated in Supplementary Figure 5, also helps me to appreciate the method's potential for manipulating intricate particle assemblies.

I am satisfied with the authors' revisions and the clarifications provided, and I now support the publication of this work in Nature Communications.

Reviewer #5

(Remarks to the Author)
I co-reviewed this manuscript with one of the reviewers who provided the listed reports. This is part of the Nature Communications initiative to facilitate training in peer review and to provide appropriate recognition for Early Career Researchers who co-review manuscripts.

# Reply to Reviewer Comments

We thank all reviewers for their careful reading of the manuscript and their highly constructive comments. Below we address each of these comments in turn. Each comment is shown in **black** font color, our reply is given in **blue**, and changes made are stated in **red**.

**Reviewer #1:**

This manuscript describes experimental studies of a protocol for organizing acoustically levitated rafts of granular matter into desired configurations. The method is inspired by optical pumping of atomic systems in which undesired stable states are driven into unstable excited states that then have some probability to relax into desired stable states. Pumping is achieved in the acoustic system by modulating the acoustic levitator's high-frequency drive with a low-frequency sine wave whose frequency and amplitude are chosen to destabilize all but the desired structure. The drive frequency, the modulation frequency and the modulation amplitude serve as control parameters for this acoustic pumping protocol. Optimal parameters are chosen based on a numerical evaluation of the interactions between pairs performed in COMSOL. The computed forces incorporate conservative wave-mediated interactions, nonconservative streaming forces and nonreciprocal wave-mediated interactions. Results of these computations are presented in Fig. 2e, Fig. 3d and Fig. 4a for increasingly complicated clusters of spheres. Experimental and numerical methods are described clearly in the Methods section.

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This study of dynamic acoustic trapping is timely, the work is original and the successful demonstration of structure selection in a complex driven system will excite a lot of interest. I recommend that this paper be published in Nature Communications.

I am particularly impressed by the demonstration in Fig. 3 of controlled switching between structures with five-fold and four-fold symmetry using nothing but the time dependence of the amplitude of a uniform plane standing wave. The demonstration in Fig. 5 that the size of large clusters can be controlled with parametric pumping creates opportunities for practical applications.

**Reply:** We very much appreciate the thoughtful evaluation and positive feedback.

Although the text is generally clear, it still would benefit from careful editing. Two examples illustrate that the issues are minor but still worth fixing: Line 194: "... when starting from 10^4 initial ..." Line 64: "More details ... is discussed ..."

**Reply:** We are grateful for the comments on text details, and we applied the following changes to the manuscript.

**Changes made** (line numbers refer to the revised paper):
Line 69: We have corrected the grammar mistake.
Line 200: We have added the missing word.

**Reviewer #2:**

In this work, the authors establish parametric pumping as a method for the configurational control of acoustically levitated particle clusters.

By modulating the amplitude of an acoustic trap at the resonant frequency of a levitated cluster and subsequently turning off the modulation, structures are first rendered unstable and then allowed to reorganize. Since the pumping only affects undesired configurations, these are eventually selected out upon repeating the process leaving a preferred configuration.

The authors first demonstrate experimentally the principle with a two particle structure, then show controlled configuration switching in a five particle cluster and finally use pumping as a way to reduce cluster size by expelling particles from the acoustic trap. In simulation, scenario's with higher particle numbers are explored, demonstrating robustness of the approach.

The presented work nicely circumvents the hard problem of navigating between fixed points of an out-of-equilibrium energy landscape, by providing a selective mechanism to break up unwanted structures. While existing approaches to the assembly of e.g. colloidal structures rely on models of the energy landscape, the presented pumping strategy only requires a priori knowledge of the vibrational spectra of cluster configurations. This constitutes a promising step towards more robust self-assembly of particulate structures, where it has been difficult to gain control over which clusters to break up and which to keep. The text and figures are very clear and pedagogical.

For all these reasons, I consider it a good fit for Nature Communications.

**Reply:** We thank the reviewer for the positive assessment of the novelty of the work, the robustness of the technical approach as well as the clarity of the text and figures.

However, I have some concerns regarding the generalization towards larger clusters and optical trapping:

· Fig 4d shows how the probability of not finding the icosahedral state falls off exponentially as a function of quench steps. Presumably this configuration was chosen for its increased stability due to symmetry. I wonder how the probability decay varies for the various other stable states: how many quench steps are needed for the least stable state to be reached?

**Reply:** We thank the reviewer for raising this question. In the manuscript, we did not explicitly study the stability of the structures (with 'stability' referring to the likelihood of remaining in the attraction basin associated with a given structure), because we effectively operate at T=0 (in our athermal systems the particle size, around 40um, makes thermal fluctuations negligible) and, importantly, we are considering non-conservative systems where potential energy landscapes are not relevant. Instead, we focus on the 'selectability' of different structures. The icosahedral state, in particular, was chosen for its pronounced gap in the state diagram, making it a compelling candidate for selection using our pump-quench method. More generally, we can most easily select structures that have little overlap with other states in their excitation spectrum (helpful in the pumping phase) and also have wide basins of attraction (helpful in the quenching phase). As a rule of thumb, we expect highly selectable states to have more unique vibrational modes and larger basins of attraction, but not in every case.

We understand the reviewer's concern about the generalizability of our method, i.e., the ability to select a more complicated state. To address this, in the revised manuscript we extended the analysis by applying the pump-quench method to control another structure in the LJ system. This new structure is shown in a newly added figure, Supplementary Fig. 5. Its state diagram exhibits greater overlap with others, making it more challenging to select. To achieve this, we use two frequencies to select this state, i.e., the method we discussed in the manuscript with the rod-and-two-spheres system. We apply one pumping cycle at this state's small peak at f_am=5.5 to destabilize other structures and another pumping cycle at f_am=7.4, targeting the icosahedron. With these two frequencies, the probability of staying outside of the target state decays more slowly than for the icosahedron, dropping 50% after 200 cycles, but it still follows an exponential manner. This aligns with our understanding of Markov models and suggests that, as long as the states' diagrams are not completely overlapping, it is possible to introduce bias and select between them (even if the bias may be small). Further details on the overlapping possibilities and their dependence on particle number and damping coefficients, were already shown in Supplementary Fig. 6 and 7.

We hope this additional analysis clarifies the potential and limitations of our approach and strengthens the case for its general applicability.

**Changes made:**
A new Supplementary Fig. 5 has been added to the supplementary material to show the generalization ability of our method for harder-to-select states. Additional text has been added to explain and analyze the data shown in this figure on Line 202-206 and Line 521-532.

· The presented strategy promises to generalize to other trapped settings such as in optics and fluidics and also to higher particle number. However, in those situations, it may not always be feasible to do FEM simulations in order to find the linear stiffness matrix, especially as the number of particles increases. How does this approach scale with larger cluster sizes? Could for instance a reduced order model of the trapped particles be used to find the stiffness matrix?

**Reply:** We appreciate the reviewer's questions. The computational complexity for the FEM simulation to determine the linear stiffness matrix should scale cubically with the particle number N, as time consumed by the 3D finite element solver scales quadratically and the number of trials for displacement scales linearly. Therefore, we agree that a reduced-order model will be very helpful in finding the stiffness matrix. This can be done by considering the symmetry of the system (like only moving one particle in the pentagon state will be sufficient, as there is permutation symmetry among the particles), or by focusing only on the relevant vibrational modes achievable in the experiments (like adapting a continuum model for the granular rafts). We believe that as long as the reduced-order model gives accurate enough vibrational frequencies, it will be a good fit for systems with larger sizes.

Another useful way of locating the vibrational frequencies in our system, as well as in other possible systems, is conducting a frequency sweep experimentally. Specifically, by applying parametric pumping to the system with a small modulating depth and a small modulating time while sweeping through different frequencies, one can observe the growth rate of vibrational modes for different structures without destroying them, and then one can use this information to determine the best combination of parameters to select structures.

**Changes made:**
We now include a discussion in Methods from line 423 to 434 on the possibility of using reduced-order models to speed up the calculation of the stiffness matrix, as well as the practical method of frequency sweeping in determining the suitable frequencies to control structures in experiments.

· In a similar vein, to what extent do the vibrational modes and growth rates depend upon the strength and nature of the nonreciprocal interactions? More generally, what is the role of non-reciprocity in enabling the growth of the vibrational modes?

**Reply:** Generally speaking, the nonreciprocal interactions alter the eigenfrequencies of vibrational modes, which in turn leads to changes in the growth rates of the modes. While we cannot tune the nonreciprocal interaction strength in our experiments and experimentally-based simulations, we can consider the following generalized framework:

A stiffness matrix K can be separated into the reciprocal part and the non-reciprocal part, and we can introduce a scaling factor α for the non-reciprocal part to study its influence as follows,
$K = K\_sym + \alpha * K\_asym$ .

With $\alpha << 1$, the non-reciprocal part acts like a small perturbation to the matrix. The eigenvalues of K will differ only slightly from those of K_sym in this case. While the eigenvalues of a symmetric matrix K_sym for a stable system are always non-negative, the direction of the shift caused by the non-reciprocal noise likely depends on the detailed structure within the matrix. This results in slight changes to the growth rates of the vibrational modes, with the direction of these changes determined by the specific structure of K.

As α increases, the likelihood that some eigenvalue shifts below zero will also increase. When α becomes sufficiently large, this effect can destabilize the structure, as negative eigenvalues correspond to unstable vibrational modes. This phenomenon highlights a potentially rich area of study, warranting further investigation into the interplay between nonreciprocity and vibrational stability.

· In fig.5, the authors show how pumping can expel particles from the trap. I wonder if a more stronger or more nonlinear trap would instead create dynamical steady states such as limit cycles. Could the authors comment on the feasibility of creating dynamical steady states through pumping?

**Reply:** This is an intriguing idea, and we believe it may be feasible to create dynamic steady states through pumping with a stronger confining trap. With a small number of particles, the system can potentially find limit cycles once the particles form some trajectories that can balance the energy input from pumping and energy output from viscous drag. When the system has a large number of particles, chaotic behaviors such as turbulent flow may emerge. Unfortunately, our current setup's confining power is not strong enough to investigate this interesting regime of dynamical states.

Minor comments:

· Line 37-38 should state that 'states […] are not isospectral, i.e. have distinguishable vibrational bands.'

**Reply:** Thank you for the correction!

**Changes made:** We updated the sentence on Line 42.

· Line 89-90 mentions that the growth rate seen in the pumping state diagram of fig2e are similar to solutions to Mathieu's equation. It would be more precise perhaps to refer the pattern seen there as an Arnold tongue.

**Reply:** Thanks for pointing this out.

**Changes made:** We now refer to the pattern as Arnold tongues on Line 96-97.

· Line 93: 'Only regions above them' is a bit vague, instead I recommend using gamma2*>1.

**Reply:** Thanks for recommending this change.

**Changes made:** We now refer to the areas as gamma2*>1 on Line 99.

**Reviewer #3 (Remarks to the Author):**

I co-reviewed this manuscript with one of the reviewers who provided the listed reports. This is part of the Nature Communications initiative to facilitate training in peer review and to provide appropriate recognition for Early Career Researchers who co-review manuscripts.

**Reviewer #4 (Remarks to the Author):**

The paper explores parametric pumping via amplitude modulation in a single-transducer system for manipulating acoustically levitated multi-particle systems. It demonstrates transitions between stable and unstable configurations, highlighting emergent dynamics and non-reciprocal interactions. The simplified setup offers an accessible alternative to phased arrays while providing insights into modulation-driven behaviour.

**Reply:** We thank the reviewer for the constructive feedback and we appreciate the opportunity to clarify the novelty of our study and address the concerns raised by the reviewer.

We emphasize that the core novelty of our study is not the dynamics of particles with non-reciprocal interactions. Instead, the novelty of our work lies in developing and demonstrating a generalizable method for selective state control through parametric pumping. This method enables precise state control by exciting undesired configurations and quenching them into the targeted one, circumventing the need to design a free-energy landscape or apply finely tuned forces on individual particles.

This work examines near-field acoustic manipulations, where particle dynamics are governed by localized gradients near the sound source. This contrasts with far-field studies (e.g., Hirayama et al., 2019; Caleap & Drinkwater, 2014) that explore broader dynamics in spatially extended fields generated by phased arrays. While the near-field focus is a noteworthy contribution, it limits the generalizability of the findings, and explicitly addressing this distinction and its implications would enhance the paper.

**Reply:** We appreciate that the reviewer contrasts our work with far-field control methods. While both the established far-field methods and the near-field method we propose here utilize modulation of the background field, they are fundamentally different in conceptual approach and in practical usage.

On the conceptual level, far-field methods modify the acoustic potential landscape set up by the primary acoustic force to generate one or more potential minima that trap particles. In phased array setups these minima can vary in time and space, allowing for steering of particles trapped in such well(s). However, being based on the primary acoustic force this approach operates on scales where the well-to-well separation is on the order of the sound wavelength or larger, and it does not control particle-particle interactions. By contrast, our near-field method explicitly focuses on manipulating particle-particle interactions via secondary forces in order to control configurations of particles that are closely spaced (separation much less than the sound wavelength). At such close spacing it becomes challenging, if not impossible, to generate sufficiently strong gradients in the primary acoustic force to steer particles.

From a practical usage perspective, far-field methods offer powerful control for multi-particle configurations extending over distances of several sound wavelengths. However, if several particles become trapped in a given well and start to interact, their local configuration cannot be controlled. By contrast, our near-field method has the advantage of precise control over particle configurations in clusters that are nearly close-packed, which is useful for, e.g., guided particle self-assembly.

While we have not explored it in the present experiments, we can envision that our near-field method can be combined with far-field methods to control individual structures in each of the potential wells and thereby achieve simultaneous assembly of the same targeted particle configuration in multiple wells.

**Changes made:**
We now added the word ‘interacting’ in the title and in lines 3-5 and 11-12 in the abstract to stress the conceptual breakthrough and practical usage of controlling interacting particles. In addition, we added lines 16-22 to the introduction to better address the difference between our method and far-field-based methods. In the discussion section, we added lines 229-232 to emphasize that our method does not require highly localized potential gradients and on lines 242-248 we added a brief discussion to indicate that our new near-field method could potentially be combined with existing far-field methods.

We also added three references on far-field approaches, including the two referred to by the reviewer:

1. Hirayama, R., Martinez Plasencia, D., Masuda, N., & Subramanian, S. (2019). A volumetric display for visual, tactile, and audio presentation using acoustic trapping. Nature, 575, 320–323.
2. Caleap, M., & Drinkwater, B. W. (2014). Acoustically trapped colloidal crystals that are reconfigurable in real time. Proceedings of the National Academy of Sciences, 111, 6226-6230.
3. Marzo, A. & Drinkwater, B. W. (2019). Holographic acoustic tweezers. Proceedings of the National Academy of Sciences 116, 84–89.

The paper highlights non-reciprocal interactions as a novel feature, but this claim feels overstated, particularly in light of the authors' prior work (Lim et al., 2024), which demonstrates that non-reciprocity naturally arises in acoustically mediated systems through field-mediated interactions rather than direct particle-particle forces. This behavior is a well-known property of multi-particle acoustic systems in the Rayleigh regime, driven by the sound field’s influence.

While non-reciprocity is an intriguing aspect of acoustic manipulation, the paper does not significantly expand on this established concept. To strengthen this aspect, the authors should provide a deeper theoretical analysis of how non-reciprocal dynamics influence particle transitions or explore broader implications and applications beyond what is already known.

**Reply:** We regret this misunderstanding of an important aspect of our paper and have modified the text to better explain why we consider non-reciprocal interactions. In short, we did not intend to focus on the novelty of non-reciprocal interactions or on how they are shaping the dynamics of the levitated particle clusters; rather, we used non-reciprocal interactions as an ideal candidate to show that our method will work in systems where free energy cannot be possibly defined.

We are not aware of non-reciprocity being a property that is well-known for multi-particle acoustic systems in the Rayleigh regime, in the sense that there is a substantial existing body of literature and a well-established theoretical understanding. While there has been some theoretical work that predicts non-reciprocity from higher order scattering interactions between two particles of different shapes or of very specific shapes (so as to enable odd Willis coupling), these effects vanish when the two particles are identical spheres. In the review paper by our group (Lim et al., 2024) cited by the reviewer, the interactions between a *pair* of two acoustically levitated particles are discussed in detail; however, the non-conservative and non-pairwise forces between multiple particles are highlighted as an open frontier of research. Only recently this year have multibody non-reciprocal interactions arising from sound scattering been predicted (based on theoretical analysis of higher order terms than previously taken into account; King et al., arXiv:2404.17410). To the best of our knowledge, for multibody non-reciprocal forces on acoustically levitated particles arising from viscous microstreaming flows no theoretical analysis exists so far. This lack of theoretical understanding of non-conservative interactions between multiple interacting particles in the Rayleigh regime highlights the difficulty of precise particle control in this regime, and this is the reason why we use it as a pertinent example to demonstrate the power of our parametric pump-quench method. We emphasize that our method does not *require* non-reciprocity in the particle interactions. Instead, we showcase that it can work with non-conservative systems as well as conservative ones.

**Changes made:**
We added text on Lines 7-9 in the abstract, Lines 47-48 in the introduction, and Line 238 in the discussion to better clarify that our method can work with a non-reciprocal system but does not require non-reciprocity.

The authors' prior work (Lim et al., 2024) offers a comprehensive framework for modeling acoustic interactions, including secondary forces, micro-streaming, and Rayleigh regime dynamics. The current paper largely reiterates these principles without substantial new contributions. Although this reference is briefly mentioned in the introduction, it is not meaningfully integrated into the main discussion. To clarify the novelty of the present study, the authors should engage more deeply with their prior work, highlighting how this paper builds upon or diverges from those earlier findings.

**Reply:** The reviewer raises concerns regarding the connection to our prior work. We wish to clarify here that the present paper, while using some of the general framework we reported on in the cited review and established in our prior research, serves a completely new purpose, namely to introduce a novel generalizable method for manipulating strongly interacting particle configurations even in the absence of a viable potential energy landscape, i.e., even in non-conservative systems.

**Changes made:**
We added a sentence on Lines 84-85, demonstrating that we use the previously established framework as a basis to develop the new control method.

Overall, this work risks being seen as incremental in scope, given the exhaustive modeling the authors have already published in May 2024 (available on arXiv since January 2024). Addressing these concerns, particularly by clarifying the novelty and integrating prior work more effectively, would greatly improve the paper's impact. However, irrespective of these improvements, I do not believe this work meets the standard or broad significance required for publication in Nature Communications.

**Reply:** In this manuscript, we introduce a novel approach that addresses critical challenges when controlling multi-particle systems in near-field and non-conservative regimes where other methods cannot be applied. This is not incremental in scope; we note that at the time our review was published (May 2024) nobody knew the extent to which parametric pumping might be applied for useful structural reconfiguration of interacting multiparticle systems and we could only speculate. We believe that the findings detailed in the current manuscript represent a significant conceptual advance with broad application potential. We demonstrate the wide-ranging applicability of our new method across different types of interactions (acoustic and Lennard-Jones), different interaction symmetries (reciprocal and non-reciprocal), as well as different system sizes (from small clusters to rafts of hundreds of particles). This shows the versatility of the parametric pumping method, which we believe can be adapted to a wide range of other physical systems with tunable interactions, including dielectric, magnetic, and optically trapped particles. As we mention at the end of the discussion section, this opens up potential applications in microrobotic assembly, defect manipulation in colloidal crystals, and directed self-assembly of complex functional materials. We hope this response clarifies the focus and novelty of our work and resolves the reviewer's concern regarding the significance and broader impact of our work.

**Changes made:**

We added text on Lines 3-5, 7-9, 229-232, and 242-248 to better emphasize the focus and novelty of our work.

**Reviewer #5 (Remarks to the Author):**

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