nature portfolio

Peer Review File

Observation of string breaking on a (2+1)D Rydberg quantum simulator

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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:

Referee #1

(Remarks to the Author)
The manuscript by Bylinskii et.al. simulated the dynamics of the 2+1d U(1) compact gauge field with Rydberg atom arrays. The paper demonstrated the breaking of string (electric field line) due to the gauge confinement effect, by experimentally tuning the strength of the string tension. I find the paper interesting and quite impressed by the experimental technique.

But I have some reservation of recommending publishing the paper on Nature, mostly for the following reason. With gapped matter fields (which is the case in the system under study I believe), the 2+1d U(1) compact gauge field is always confining, except for the fine-tuned "RK" point. Hence there is actually no "deconfined phase" v.s. "confined phase"; the observed string breaking is probably a finite size effect, meaning if the created string is long enough, it would always break. When one increases the string tension, the confinement length will be shorter, and when the confinement length is smaller than the system size, the created string would break.

Hence I feel what was observed is interesting, but probably not an intrinsic feature associated with a real phase in the thermodynamics limit.

Of course, I am willing to reconsider if I misinterpreted the results of the paper.

Referee #2

(Remarks to the Author)
In their manuscript, González-Cuadra et al., report on the observation of string breaking in a programmable Rydberg quantum simulator. They implement
a (2+1)D lattice gauge theory (LGT) with dynamical matter using individual atoms in a Kagome lattice and the Rydberg blockade mechanism. This allows them to obtain a local U(1) symmetry and a linear confining potential between pairs of charges. They adiabatically prepare the ground state of the system and study the phase diagram. Afterwards, via local control, they perform quantum quenches of the experimental parameters to observe string-breaking dynamics of initially prepared configurations.

The possibility of efficiently implementing LGTs in quantum simulators and computers is currently an active field of research. These efforts are motivated by the potential access to non-perturbative phenomena and real-time dynamics, which are otherwise difficult to study using classical methods for large systems. The present manuscript tackles precisely this topic, by providing a means to study string breaking and confinement phenomena for the first time in a two-dimensional configuration. As such, their results are likely to be of interest for a broad community ranging from high-energy and early-universe physics to quantum algorithms and will attract a lot of interest in the Rydberg atom platform.

Overall, the manuscript is very well written and understandable. The results are impressive and potential implications for the study of LGTs are remarkable. The results are robust and supported by calculations. In addition, as mentioned in the final note, these results are very timely, since similar experiments have very recently been performed with ions and superconducting qubits in analog and digital modes. For all these reasons I recommend publication in Nature.

Nonetheless, I have some comments/questions I would like the authors to consider before publication:

1. The quasi-adiabatic sweep employed in Fig. 1e may not be the optimal protocol given the decoherence of the setup. Previous experiments at Harvard/MIT demonstrate that adopting optimal control techniques can improve ground state preparation. Are these techniques useful here?

2. In Ref. 6, there is a discussion about the appearance of a stripe phase as a precursor to the nematic phase and about the role of quantum fluctuations. Quantum fluctuations are barely discussed in the present manuscript and there is no explicit mention to these phases in quantum magnetism. Is there a connection we can extract from these two different models?

3. The paper stresses the fact that, together with Ref. 27, is the first realization of two-dimensional geometries to study LGTs. Perhaps it should be mentioned in the conclusions how the dynamics or equilibrium properties of string breaking differ fundamentally in (2+1)D compared to (1+1)D.

4. In the exploration of the string breaking phase diagram, the authors mention that the mean energies of the six configurations corresponding to the same length are different and thus the measured probabilities are different. I was wondering if the finite size of the system has also some boundary effects here. I would appreciate a discussion about that in the section.

5. Throughout the paper, experimental results are supported by calculations. I am curious to know what the limits in system sizes are to be calculated classically and what sizes are needed for the “quantum machine” to be competitive against MPS.

6. Finally, in the section of string breaking dynamics, I would appreciate a discussion about relaxation time, thermalization and the connection to quantum scars observed in previous experiments.

Version 1:

Reviewer comments:

Referee #2

(Remarks to the Author)
I am well satisfied with the authors's replies to my questions and the issues raised by the other referee. Overall, I find the manuscript demonstrates the potential of Rydberg platforms to simulate LGTs in 2D, and I am sure many other experiments will follow. From this point of view, I believe Nature is the best suited journal to convey the results to a broad community and I therefore support publication.

Referee #3

(Remarks to the Author)
The authors have presented a fascinating analysis of a particular simplified (2+1)D LGT quantum simulated via a Rydberg atom quantum simulator. The present a quasi-adiabatic protocol to prepare the initial string state and then study its dynamics after a quench. The analysis is performed carefully, and it is solid, well presented, and most probably correct (even though, of course, I have not repeated the calculations independently).

I have read the previous referee reports and the author's answer, which I find satisfactory. The manuscript is highly timely and is at the level of a recent manuscript that presented a similar analysis performed on a superconducting quantum computer, witnessing the interest of the scientific community in this line of research. Indeed, simulating complex physical phenomena is considered one of the most promising applications of current and future quantum computers and simulators. This work is a prominent example of this research line and sets a new standard for the field.

For the above-mentioned reasons, I recommend publication of the manuscript after the authors have considered one last point I would be interested in hearing their opinion on: similar analysis on excitation strings in spin systems showed that the string can be represented as a CFT on top of the ground state (see, e.g., F. Tschirsich, et al SciPost Phys. 6, 028 (2019)). Is this picture also confirmed in this case? Can the authors say something about that? It would be very interesting, and it should be possible to assess it at least in the numerical study. simulations.

Minor point: at line 346, there is a double "the" before "relative shift".

Response to Referees

We thank both Referees for taking the time to read and assess our manuscript. As detailed below, we have taken their constructive feedback into account and revised our manuscript accordingly. We believe that the improved version of our paper is now eligible for publication in Nature.

Response to Referee 1

Referee

The manuscript by Bylinskii et.al. simulated the dynamics of the 2+1d U(1) compact gauge field with Rydberg atom arrays. The paper demonstrated the breaking of string (electric field line) due to the gauge confinement effect, by experimentally tuning the strength of the string tension. I find the paper interesting and quite impressed by the experimental technique.

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Hence I feel what was observed is interesting, but probably not an intrinsic feature associated with a real phase in the thermodynamics limit.

Of course, I am willing to reconsider if I misinterpreted the results of the paper.

Our reply

We are pleased to learn that the Referee finds our paper of interest and is impressed by the experimental results, which report the first observation of $(2+1)$D string breaking in a U(1) LGT in both equilibrium and quench dynamics with an analog quantum simulator. We understand the referee's only concern to be around their interpretation of string breaking in the language of quantum phase transitions, which are not the target of this study, and we believe we address this concern below and in clarifying this in the updated manuscript.

The Referee rejects our paper because (i) the model that the atomic system naturally realized in the experiment supports "only" a confined phase vs. also displaying deconfined phase, and (ii) the Referee calls string breaking a "finite size" effect, as something not associated with an intrinsic feature of a real phase in the thermodynamics limit.

While the referee's statements are technically correct, in particular when seen from a condensed matter perspective, we respectfully disagree that these are the relevant criteria to evaluate our study of string breaking. First, string breaking is a phenomenon in the regime of the confined phase - as realized in the experiment. Second, the phenomenon of string breaking is intrinsically a finite-length effect, as pointed out by the Referee. We see this as a fundamental aspect of the phenomenon to be studied, in particular in real-time dynamics. As we write in the introductory paragraph of our manuscript, we see the motivation and questions as coming more from the high-energy physics perspective, where this is the relevant regime, and this is what our study is about. We elaborate on these points in more detail below.

The Referee is correct in pointing out that part of our writing in the original version of our manuscript may be somewhat misleading: indeed, the use of thermodynamic language, like phase diagrams in the context of string breaking is not appropriate. As initiated by the Referee, we have carefully revised our manuscript to sharpen both the language, motivations and perspective, and thus the focus of our string breaking study. We are hopeful that the Referee finds the revision of the manuscript a significant improvement and clarification of the purpose and results of our work.

Confinement vs deconfinement.– In our opinion, there are many good reasons to study the dynamics of gauge theories. From a condensed matter perspective, there is a strong focus on the realization of deconfined phases that display topological order whose patterns of long-range entanglement may even be technologically relevant. This is not the point of our work.

Here, we instead take a particle physics perspective, intentionally focusing on a confined phase where the low-energy excitations are tightly bound mesons and extended string-like objects only exist at high energies. This situation is reminiscent of what happens in QCD, which is a confining theory at low temperatures and densities, whereas individual quarks or gluons can fundamentally only be detected indirectly in high-energy processes. As the Referee points out correctly, we deal with a 2+1d U(1) lattice gauge theory which hosts a confined and no deconfined phase, but as argued above this is precisely the regime we are interested in.

String breaking and thermodynamic limit.– In this confined phase, which is well defined in the thermodynamic limit, we first probe these low-energy excitations by introducing defects (static charges) that pin the strings to certain (finite-size) regions. The referee is indeed correct that these parameter regions where we find broken/unbroken strings do not represent distinct thermodynamic phases. Although we investigate the ground state corresponding to these configurations, this is just a way to probe the properties of the meson/string configurations that are relevant at higher energies, i.e., confinement between charges, string breaking for a certain length scale, etc. We note that this procedure is similar to the one employed in lattice QCD, where static charges are also introduced to calculate the confining potential, the corresponding string tension and the breaking of flux strings [see, e.g., Bissey et al., "Gluon flux-tube distribution and linear confinement in baryons" Phys. Rev. D, 76(11), 114512 (2007); Bali et al., "Observation of string breaking in QCD", Phys. Rev. D, 71(11), 114513 (2005); Bulava et al., "String breaking by light and strange quarks in QCD", Phys. Lett. B, 793, 493-498 (2019)]. In the revised version of the manuscript, we make this point clearer to avoid confusions concerning the interpretation of string configurations as thermodynamic phases of matter (see changes below).

We however object to the classification of string breaking as just a finite-size effect. By definition, a finite string tension dictates a linear growth in energy with the length of a finite string. String-breaking occurs when this energy exceeds the one required to produce a particle-pair. This sets a string-breaking length scale that depends on the rest mass of the produced particles. In this sense, string-breaking is always a finite string-length effect (and we note that this is also the case when the model presents a deconfined phase). Nevertheless, it is a real phenomenon that can occur in a thermodynamically large environment, as in the case of QCD. Importantly, as we demonstrate experimentally using our ground-state preparation protocols and backed up by our numerical simulations, our setup allows us to tune all relevant involved length scales set by the string-tension (controlled by the Rydberg blockade radius), the particle rest mass (controlled by the detuning) and the total system size. Within the experimental limitations this enables the realization of strings and their breaking at arbitrary length scales.

Relevance in high-energy physics.– Finally, a crucial further step in our work is the study of string-breaking out of equilibrium. In the case of QCD, the theoretical understanding of non-perturbative aspects of hadronization in this regime remains incomplete, such that that semi-classical phenomenological models [e.g. the so-called "Lund model", Andersson et al., "Parton fragmentation and string dynamics", Physics Reports, 97(2-3), 31-145 (1983)] are employed in event generators routinely employed to describe high-energy particle collision experiments [see, e.g., Bierlich et al., "A comprehensive guide to the physics and usage of PYTHIA 8.3", SciPost Physics Codebases, 008]. Improving our understanding of the real-time dynamics of string-breaking is therefore directly relevant to a better understanding of high-energy heavy-ion collisions [see, e.g., Kharzeev/Loshaj, "Jet energy loss and fragmentation in heavy ion collisions". Phys. Rev. D, 87(7), 077501 (2013); Florio et al., "Real-time nonperturbative dynamics of jet production in Schwinger model: Quantum entanglement and vacuum modification", Phys. Rev. Lett., 131(2), 021902 (2023); Altmann et al., "Towards the understanding of heavy quarks hadronization: from leptonic to heavy-ion collisions", The European Physical Journal C, 85(1), 1-59 (2025)]. In our experiment, we probe related scenarios with quenches where long strings (connecting dynamical charges) are created as highly excited states on top of the vacuum, which then dynamically break down to smaller strings/excitations. Of course, our setup can only be interpreted as a very distant cousin of QCD. Nevertheless, it shares some features of string-breaking, as discussed above. In light of this similarity, we view our experiment as one of the first of its kind which opens the door to experimentally studying outstanding questions about the real-time dynamics of confinement and string-breaking with analog quantum simulators. In contrast to previous works, here we take the important step from 1D to higher spatial dimensions where the dynamics of gauge fields starts to become important. While here we probe some aspects of string breaking, future experiment can explore this phenomenon further by investigating e.g. the thermalization dynamics of broken strings at longer times. In the revised version of the manuscript, we have added some of the references mentioned above to make a clear connection between string breaking and particle-physics experiments.

Response to Referee 2

Referee

In their manuscript, González-Cuadra et al., report on the observation of string breaking in a programmable Rydberg quantum simulator. They implement a (2+1)D lattice gauge theory (LGT) with dynamical matter using individual atoms in a Kagome lattice and the Rydberg blockade mechanism. This allows them to obtain a local U(1) symmetry and a linear confining potential between pairs of charges. They adiabatically prepare the ground state of the system and study the phase diagram. Afterwards, via local control, they perform quantum quenches of the experimental parameters to observe string-breaking dynamics of initially prepared configurations.

The possibility of efficiently implementing LGTs in quantum simulators and computers is currently an active field of research. These efforts are motivated by the potential access to non-perturbative phenomena and real-time dynamics, which are otherwise difficult to study using classical methods for large systems. The present manuscript tackles precisely this topic, by providing a means to study string breaking and confinement phenomena for the first time in a two-dimensional configuration. As such, their results are likely to be of interest for a broad community ranging from high-energy and early-universe physics to quantum algorithms and will attract a lot of interest in the Rydberg atom platform.

Overall, the manuscript is very well written and understandable. The results are impressive and potential implications for the study of LGTs are remarkable. The results are robust and supported by calculations. In addition, as mentioned in the final note, these results are very timely, since similar experiments have very recently been performed with ions and superconducting qubits in analog and digital modes. For all these reasons I recommend publication in Nature.

Our reply

We thank the Referee for the positive comments to our work, as well as for the recommendation to publish the manuscript in Nature.

Referee *Nonetheless, I have some comments/questions I would like the authors to consider before publication:*

1. The quasi-adiabatic sweep employed in Fig. 1e may not be the optimal protocol given the decoherence of the setup. Previous experiments at Harvard/MIT demonstrate that adopting optimal control techniques can improve ground state preparation. Are these techniques useful here?

Our reply The referee is correct that optimal control can generally enhance the yield in adiabatically preparing the states in the confined phase of our model. We did test these approaches, but decided not to rely on them for the results that are the focus of the paper, as the observed enhancements did not significantly improve the data quality or affect our conclusions, and the techniques come at a significant cost in data overhead. A more detailed explanation follows below.

Besides linear detuning sweeps, we tested several other sweep models featuring a slower sweep rate around the confined phase boundary at the cost of a faster sweep rate away from it. We observed moderate enhancement in prepared string probabilities, only when the sweep model parameters were experimentally fine-tuned for each corresponding point in the confined phase diagram. Below is our commentary on the costs and benefits of this for each result shown in the manuscript:

Confined phase boundaries and string breaking boundaries in Fig.1h, 2c, 2e, 2f and Ext. Dat. Fig. 7: The state probabilities in these figures are less important than the location of these boundaries. Identifying the boundaries is unambiguous when using a linear detuning sweep, whereas the nonlinear sweep protocols described above fail when ending near a phase boundary (where the sweep model itself should be changed). Furthermore, reconstructing these diagrams using the nonlinear sweep protocols is significantly more data intensive, as all their parameters need to be separately optimized for each point, and the sensitivity to this optimization could lead to significant inhomogeneities across the 2D plots.

Probability distribution over the multiple strings in the ground state in 2D, Fig. 2g and 2h: We verified that the nonlinear detuning sweep protocols described above indeed moderately enhance the total probability, but do not alter the distribution. We decided to include data obtained using a simple linear sweep here, in order to be consistent with the phase diagrams shown in Fig. 2e and 2f, which were obtained using the linear detuning sweeps for reasons described in the paragraph above.

Individual string state preparations in Fig. 1e, 1f, 1g and Ext. Dat. Fig. 2, using the protocol in Ext. Dat. Fig. 1b. This protocol already has a number of parameters between the simultaneous global and local detuning sweeps, which were optimized to yield the near perfect Rydberg excitation configurations corresponding to the targeted string and broken string states, as can be seen in the figures. In the paper, we did not present the quantitative fidelities of these states, which could possibly be further improved by using more sophisticated nonlinear sweep models for the global and local detuning. States prepared this way were not, however, the starting point of our dynamics studies, and any enhancement would not affect the conclusions from the presented data.

Time dynamics data of string breaking, Fig. 3 and Ext. Dat. Fig. 5. We tested the enhancement of string preparation probability by the nonlinear sweep protocols and did not observe a significant effect for the system sizes studied here, and opted for the simpler linear detuning sweep state preparation protocol to reduce data cost. We expect any enhancement to manifest in a slightly rescaled y-axis in the time dynamics plots, without effects on the time-domain patterns observed.

Many-body spectroscopy resonances, Fig. 4. Besides the argument in the above paragraph, spectroscopy information is in the peak locations, insensitive to the vertical scale of the signal.

Referee: *2. In Ref. 6, there is a discussion about the appearance of a stripe phase as a precursor to the nematic phase and about the role of quantum fluctuations. Quantum fluctuations are barely discussed in the present manuscript and there is no explicit mention to these phases in quantum magnetism. Is there a connection we can extract from these two different models?*

Our reply:

Both Ref. 6 and our work consider the same model, this is, Rydberg atoms on a Kagome geometry. As the referee points out, and as it was investigated in Ref. 6, this model presents other phases apart from the nematic phase studied here, such as the stripe phase. These other phases can also be interpreted in the LGT picture by applying the same mapping we consider here, but might require, for instance, matter particles with higher charges. The reason why we decided to focus in the nematic phase is because the LGT description, with charges and strings as defined in our manuscript, provides an excellent effective theory for the ground state and all low-lying excitations. Within this low-energy limit, it is straightforward to show that the charges present a confining potential due to long-range Rydberg interactions. This appears to be more complex and may not be the case in other phases, such as the stripe phase of the model.

Regarding quantum fluctuations, it is indeed true that deep in the nematic phase (the vacuum of our LGT) the ground state is close to a product state and therefore has low entanglement. However, the situation changes as we approach its phase boundaries, a region that we scan when we study string breaking in equilibrium [see for example Fig. 2(g)]. We have added a sentence in the "String breaking in equilibrium section" to stress this point. Finally, quantum fluctuations are also present in the quench experiments, as we start with high-energy states that evolve in time after the quench.

Referee: *3. The paper stresses the fact that, together with Ref. 27, is the first realization of two-dimensional geometries to study LGTs. Perhaps it should be mentioned in the conclusions how the dynamics or equilibrium properties of string breaking differ fundamentally in (2+1)D compared to (1+1)D.*

Our reply: In (2+1)D, strings can not only break but also fluctuate between different string configurations. In our equilibrium experiments, we investigate this interplay. We have now added a sentence to the discussion section stressing this point.

Referee: *4. In the exploration of the string breaking phase diagram, the authors mention that the mean energies of the six configurations corresponding to the same length are different and thus the measured probabilities are different. I was wondering if the finite size of the system has also some boundary effects here. I would appreciate a discussion about that in the section.*

Our reply:

The difference in energy between strings is not a finite-size artifact. In the classical limit, the string energies can be calculated exactly, and this energy difference remains for an infinite system. The difference stems from longer-range Rydberg interactions, making the strings to "self-interact", resulting in an energy contribution that not only depends on the string length but also on its shape. Although finite-size effect modify the string energies, these qualitative features remain. We have now added a sentence to that section mentioning this.

Referee: *5. Throughout the paper, experimental results are supported by calculations. I am curious to know what the limits in system sizes are to be calculated classically and what sizes are needed for the "quantum machine" to be competitive against MPS.*

Our reply: The MPS simulations employed to calculate real-time dynamics were already challenging even for a system with 39 atoms, where each quench evolution took more than one day on a computing cluster. We expect that similar or longer dynamics for a system of $\mathcal{O}(100)$ atoms will reach the boundary of what is accessible with classical methods. Quantum simulators can already target those sizes, and they can maintain coherent during those timescales. However, for them to be competitive with classical methods at the quantitative level, the error sources have to be reduced. Although this is challenging for analog simulators in the absence of error correction, in the outlook we comment on possible ways to reduce the main error sources, and detail them in the Method section.

Referee: *6. Finally, in the section of string breaking dynamics, I would appreciate a discussion about relaxation time, thermalization and the connection to quantum scars observed in previous experiments.*

Our reply:

In the classical limit, for large values of the detuning, the string breaking resonance can be understood as a high-order process, where the system passes virtually through different intermediate states from the initial unbroken string to the (on-resonance) broken one. Since the number of intermediate states grow with the initial string length, the timescales for this process will be exponential with the length. In our experiment, we are not in the classical limit, but in a regime with stronger quantum fluctuations. While the presence and location of a resonance confirmed by the experimental results matches the theoretical prediction, we do not expect the semiclassical argument to correctly reproduce the relaxation time. This is indeed an interesting question that would require considering larger systems as well as longer simulation times, and that we would be interested in tackling in future experiments. We have added a sentence about the exponential dependence of the string breaking timescale, as well as a sentence in the outlook regarding the investigation of these questions in future experiments.

Connection to quantum scars.

The model we implement has a limit that approaches conditions supporting approximate quantum scarring dynamics. In particular, as shown in [Phys. Rev. X 10, 021041 (2020)], a 1D U(1) lattice-gauge theory, the quantum link model, and the PXP model that hosts quantum scars [Nat. Phys. 14, p. 745-749 (2018)] behave equivalently. Thus, in the case where we consider the linear string, some of the physics of [Phys. Rev. X 10, 021041 (2020)] applies, and if the confinement is very weak, one expects the appearance of approximate quantum scars. Quantum scar lifetime would be finite and quickly decaying with confinement energy. The relation to quantum scars is lost in cases of either 1D strings with strong confinement or 2D strings, and we thus experimentally probe distinct dynamical regimes compared to quantum scar experiments.

List of changes

We again thank both Referees for their careful reading of our manuscript and their constructive criticism of our work. We hope that our responses have answered all questions satisfactorily. Below, we give a brief list of major changes motivated by the Referees' reports. We further attach a highlighted version of the revised manuscript, where all changes are indicated.

Referee 1

Changes to avoid confusion interpreting the regions of broken/unbroken strings as thermodynamic phases of matter.

- In the abstract, we changed the sentence "We experimentally map out the corresponding phase diagram by adiabatically preparing the ground state of the atom array in the presence of defects, and observe substructure of the confined phase, distinguishing regions dominated by fluctuating strings or by broken string configurations." to "We experimentally probe string breaking in equilibrium by adiabatically preparing the ground state of the atom array in the presence of defects, distinguishing regions within the confined phase dominated by fluctuating strings or by broken string configurations."
- In the last paragraph of the introduction, we changed the sentence "This enables mapping an equilibrium phase diagram of broken and unbroken strings in $(2+1)$D, using a combination of local control and quasi-adiabatic state preparation." to "This enables us to probe string breaking in equilibrium by preparing broken and unbroken strings in $(2+1)$D, using a combination of local control and quasi-adiabatic state preparation."
- In the last paragraph of the second section, we changed the sentence "In the following, we employ the Rydberg atom array to investigate this string breaking phase diagram experimentally." to "In the following, we employ the Rydberg atom array to investigate experimentally the equilibrium properties of string breaking."
- In the same paragraph, we added the sentence "We note that this equilibrium string breaking phenomenon is not a phase transition in the thermodynamic limit, and that static charges are used here to probe the confining properties of the theory, as it is usually done for QCD."
- We changed the title of the third section from "String breaking phase diagram" to "String breaking in equilibrium".
- We included some of the references mentioned in the answer to the Referee to the manuscript.

Referee 2

- We added a sentence in the "String breaking in equilibrium" section to stress the role of quantum correlations.
- We added a sentence to the discussion section on the interplay between string fluctuations and string breaking.

- We added a sentence at the end of the "String breaking in equilibrium" section to comment on the effect of finite-size effects to the energy difference between different string configurations.
- We added a sentence in the outlook about the investigation of thermalization dynamics in future experiments.

Response to Referees

We thank both Referees for taking the time to carefully assess our revised manuscript. We are very encouraged by the positive feedback. We also appreciate the insight from Referee 3 regarding strings in spin systems, and comment on it below.

Response to Referee 2

Referee

I am well satisfied with the authors' replies to my questions and the issues raised by the other referee. Overall, I find the manuscript demonstrates the potential of Rydberg platforms to simulate LGTs in 2D, and I am sure many other experiments will follow. From this point of view, I believe Nature is the best suited journal to convey the results to a broad community and I therefore support publication.

Our reply

We thank the referee for carefully considering the revised manuscript and our replies to the previous round of comments. Thank you for the positive feedback and the recommendation to publish.

Response to Referee 3

Referee

The authors have presented a fascinating analysis of a particular simplified (2+1)D LGT quantum simulated via a Rydberg atom quantum simulator. The present a quasi-adiabatic protocol to prepare the initial string state and then study its dynamics after a quench. The analysis is performed carefully, and it is solid, well presented, and most probably correct (even though, of course, I have not repeated the calculations independently).

I have read the previous referee reports and the author's answer, which I find satisfactory. The manuscript is highly timely and is at the level of a recent manuscript that presented a similar analysis performed on a superconducting quantum computer, witnessing the interest of the scientific community in this line of research. Indeed, simulating complex physical phenomena is considered one of the most promising applications of current and future quantum computers and simulators. This work is a prominent example of this research line and sets a new standard for the field.

Our reply

We thank the Referee reviewing the revised manuscript, the prior comments, and our responses. We appreciate the positive response and agree on the relevance and timely nature of the work.

Referee *For the above-mentioned reasons, I recommend publication of the manuscript after the authors have considered one last point I would be interested in hearing their opinion on: similar analysis on excitation strings in spin systems showed that the string can be represented as a CFT on top of the ground state (see, e.g., F. Tschirsich, et al SciPost Phys. 6, 028 (2019)). Is this picture also confirmed in this case? Can the authors say something about that? It would be very interesting, and it should be possible to assess it at least in the numerical study/simulations.*

Our reply

We thank the referee for pointing out this connection. On general grounds, one expects that a fluctuating flux string can be described by an effective conformal field theory [Luescher, Nuclear Physics B, 180, 317 (1981)], which also underlies the work of Tschirsich et al. In principle, this could also be studied in the present setup. For example, one could measure the ground state energy $V(d)$ of a long string of length d (compared to the case without static charges), which is expected to scale as

$$V(d) = \sigma d - \frac{\gamma}{d} + \dots$$

with σ the string tension. The sub-leading correction $\propto \gamma$ is a characteristic universal fingerprint of the gapless transverse excitations. Unfortunately, this also shows that this is a very small correction that is experimentally quite challenging to reveal. An alternative - albeit also demanding experimentally - would be to measure entanglement entropies using, e.g., the toolbox of randomized measurements [Elben et al., Nature Reviews Physics, 5, 9 (2023)]. In any case, it is important that transversal string fluctuations are strong enough and whether this happens in the present model is an open question. In technical terms, the model needs to undergo a so-called roughening transition. Here, the situation is further complicated by the fact that string-breaking occurs for any sufficiently long string. We are currently pursuing a purely theoretical study focusing on these question for the present and related models [see also Krinitsin et al., arXiv:2412.10145, Xu et al., arXiv:2503.19027 for recent theoretical studies along similar lines].

Referee: *Minor point: at line 346, there is a double "the" before "relative shift".*

Our reply:

We thank the referee for the attentiveness, and have corrected the typo in the final version of the manuscript.