nature portfolio

Peer Review File

Emergence of collective oscillations in massive human crowds

Corresponding Author: Professor Denis Bartolo

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)
A. Summary of the key results:

The authors present empirical results for motion in large crowds. Data obtained from videos taken at a large festival in Pamplona is analyzed based on automated detection of motion of heads. By averaging, the time evolution of density, velocity fluctuations and other relevant quantities are obtained. These quantities are analysed for emergent dynamics. Self-organized collective oscillations are found beyond a critical density. The authors suggest a theoretical explanation for the findings based on the idea that crowds can be described as frictional matter.

B. Originality and significance:

The topic is very interesting and concerns an important open problem in crowd dynamics. However, similar studies have been performed before, e.g. at the Haj in [15] (see also Johansson et al., Advances in Complex Systems 11 (2008)) where the concept of "crowd turbulance" has been introduced. Although this concept can be seen critically, especially the choice of terminology ("turbulence"), similar observations have been made in other works (e.g. Wang et al., Procedia Engineering 84 (2014)). A related concept are "crowd-quakes" (Ma et al., JSTAT (2013) ; Lian et al., Physica A 452).
It can be argued that the observations at the Hajj are for a (slowly) moving crowd, but nevertheless a comparison with these findings would be desirable. It is not unreasonable to expect that the relevant mechanisms for self-organization in a standing and a slowly moving crowd are very similar. A static crowd
scenario that has been studied in much detail is the Love Parade disaster. Here also a large literature exists.

C. Data & methodology: validity of approach, quality of data, quality of presentation:

The data has been analysed carefully, using state-of-the-art techniques. Potential problems in the detection, e.g. occlusion and other obstructions (Fig.1f), have been reduced by applying machine learning based methods.

D. Appropriate use of statistics and treatment of uncertainties

Statistics of the extracted data has appropriately been determined. In Fig.1a one can clearly see large shadow effects that make distinction of heads difficult. How has this problem been addressed?

E. Conclusions: robustness, validity, reliability:

The conclusions presented are based on a single scenario, for which data of 3 different years have been analyzed. The comparison of the 3 years shows that the results are robust, at least for this scenario. However, it is unclear how this generalizes to other settings. It has not been discussed in much detail
how general the findings are.

The theory presented explains some observations correctly. On the other hand, it becomes clear that something is missing. Fig.3a shows that the peak structure is reproduced, but the behavior outside of the peaks is not described well.
I am not fully convinced by the theoretical approach as several points are not considered, as well as alternative theories. At high densities the possible motion is strongly determined by sterical restrictions, e.g. due to the body shape. It seems that the theory over-emphasizes the role of friction over the
relevance of interactions between the individuals.

F. Suggested improvements: experiments, data for possible revision:

Why is 0.1 chosen as critical value for correlations (page 3)? Have other values been tested? What is the influence of the choice of this parameter?

G. References: appropriate credit to previous work?:

A proper discussion of previous related work, e.g. on crowd turbulence and crowd quakes, is missing (see above). There are several related studies in the context of crowd disasters, e.g. the Love Parade disaster. Are these findings compatible with those presented here?
Furthermore, there is a vast literature on "synchronization" (e.g. rhythmic applause, Mexican wave,...)
that could be interesting to explore. General results for the synchronization of oscillators have been obtained that could be useful. See e.g. the (old) review by Boccaletti et al., Phys. Rep. 366.

H. Clarity and context: lucidity of abstract/summary, appropriateness of abstract, introduction and conclusions:

There is a certain redundancy of non-essential information, e.g. in Introduction. The presentation could be more compact. Also pointers to general reviews and books on pedestrian and crowd dynamics would be useful for readers not so familiar with the topic.
For me the balance between theory and analysis of empirical data is not convincing. The focus should be much more on the empirical results. Currently the theory has too much weight and its presentation could easily be compactified.

Minor points concerning the presentation:
Considering previous studies mentioned above, some statements in the Abstract appear to be a little exaggerated, e.g. "lack quantitative characterizations of these emergent dynamics". Although it is true that more and better data is needed, it is not correct that no quantitative results exist.
Also a statement like "hitherto unpredictable motion" is somewhat misleading. The motion of individuals
can also not be predicted by the present approach!
On page 3, line 106, it is emphasized that the fundamental diagram approach does not apply to massive crowds. While this is true, other quantities have been suggested to characterize such crowds quantitatively, e.g. by Zanlungo et al., Transp Res Part C 148, or Cordes et al., PNAS Nexus 3.

Recommendation:

The topic is certainly very interesting and highly relevant. However, the authors have not convincingly shown that their results are a real breakthrough in the field. Similar observations have been made earlier under the name of crowd turbulence or crowd quakes. The finding of an orbital-type motion is, to my knowledge, new, but in some sense "a detail". Furthermore it is unclear how the findings presented generalize to other settings, e.g. a typical concert scenario in a stadium.
The results certainly deserve publication (after the comments above have been considered), but in a more specialised journal where it reaches the relevant audience more efficiently.

Referee #2

(Remarks to the Author)
Key results: In their research, Professor Bartolo and his co-authors empirically iden¬tify a novel phase transition in massive crowd dynamics during the annual festival of San Fermìn in Pamplona, Spain, which gathers more than 5,000 participants each year. They collected measurements of crowd flow and density fields through video analysis in 2019, 2022, and 2023. The data were collected one hour before the festival began in a 50×20 meter area, where the density gradually increased from a slight density to an ultra-dense crowd, reaching up to 9 pedestrians per square meter locally. The empirical findings clearly demonstrate a novel phase transition from a static dilute crowd until up to 4 pedes¬trians per square meter, to dynamic crowd behaviour characterized by large oscillatory patterns and local chirality. Subsequently, they developed a mean-field crowd mechan¬ics model based to reproduce and comprehend the spontaneous symmetry breaking. The model, which is stochastic and nonlinear, describes dilute crowd dynamics around a fixed point, as well as limit cycles that exhibit remarkable similarities to the observed chiral oscillatory patterns. The authors further analyse the stability of both the fixed point and the limit cycles, revealing an interesting interplay between friction γ and windsock coeffi¬cients β that can be interpreted physically.

Validity: From my perspective, the manuscript does not have flaws which should pro-hibit its publication.

Originality and significance: Despite considerable interest in civil, safety, and traffic engineering, there is a scarcity of empirical observations and modelling of ultra-dense crowd dynamics in the existing literature. This study makes a substantial contribution to these fields by presenting novel empirical and modelling outcomes in a clear, motivated, convincing, and sharply focused manner. In my opinion, these results will attract imme-diate attention within these disciplines. Furthermore, they may also hold relevance in the realm of active material physics.

Data & methodology: The quality of the data is satisfactory, and their presentation is excellent. Furthermore, the methodologies are rigorously detailed in the manuscript. In addition to preliminary snapshots and basic plots that facilitate the visualization of density and velocity fields, the data analysis incorporates correlation and spectrum analyses for velocity, orientation, and kinetic energy files, allowing for the characterization of changes in crowd dynamics in a comprehensible and convincing manner. In the modeling section, the comparison of the proposed spontaneous symmetry breaking model to a harmonic and a chiral oscillator to justify the modeling approach is particularly noteworthy and offers valuable insights.

Appropriate use of statistics and treatment of uncertainties: I didn't identify any concerns regarding the misuse of statistics or the treatment of uncertainties within the manuscript.

Conclusions: In my opinion, the conclusions drawn in the manuscript regarding crowd dynamics at the Festival of San Fermì are robust, valid, and reliable. However, it could be beneficial to contextualize the festival situation before extrapolating these findings to crowd dynamics in general. The authors note in the Methods section that "Before this event, no external guidance dictates the dynamics of the crowd. No acoustic, visual, or mechanical signal coordinates the motion of the crowd." Yet, the context is clearly festive, with the majority of the crowd that seems composed of young men. What are their moti¬vations? They likely aim to celebrate the festival and are probably excited by the event. To what extent does this context influence the observed dynamics? Could they intentionally aim to initiate crowd movement?
As far as I know, some experiments conducted in 2013 with up to 600 pedestrians in a 10×10 meter area delimited by borders didn't reveal any oscillatory patterns (see DOI: 10.1093/pnasnexus/pgae120, Appendix A, "Waiting" scenario).

Suggested improvements:
1. As mentioned above, I would like to suggest providing a more precise contextual-ization of the festival environment, including details about the composition of the crowd and the motivations of the participants.
2. Another comment pertains to the festival's context, particularly regarding the size of the area. Could we anticipate that the size of the oscillatory patterns depends on the size of the area, or do they possess a characteristic size? Additionally, is there a critical system size for the emergence of the oscillatory patterns, and does the critical density level (here approximately 4 pedestrian per square meter) depend on the size of the system? These questions are not trivial to answer, but perhaps identifying the most unstable wavelength in the stability analysis or conducting simulations with the proposed crowd model could provide valuable insights for the reader.
3. I couldn't determine whether the stability condition 9 < 'y holds irrespective of 'yp, or only when 'yp is significantly greater than 'y. Regarding the model's structure, I would anticipate that 'yp influences the dynamics, and stability is likely constrained by this parameter as well. Providing additional information on this aspect could be beneficial for the reader.
4. I would also recommend providing more interpretation of the parameters 'y and 9, as well as the stability condition, in relation to the behavior of pedestrians, partic-ularly in connection with the concept of social and pushing forces commonly used in microscopic pedestrian modelling. Such insights could assist the reader in better understanding the physics underlying the proposed crowd model.
5. I couldn't ascertain how the local density is estimated. If this information was indeed not provided, it should be included for clarity and reproducibility purposes.

References: To my view, the manuscript references previous literature appropriately.

Clarity and context: I found the abstract to be clear, accessible, and easily understand-able. Overall, the abstract, introduction, and conclusions are well-suited and appropriate.

Inflammatory material: I didn't identify any language in the manuscript that could be deemed inappropriate or potentially libelous.

Diversity, equity and inclusion: I don't raise any concerns regarding potential impacts on diversity, equity, and inclusion within the manuscript.

Part outside the scope of your expertise The content of the manuscript aligns well with my expertise. I was able to assess it fully.

Referee #3

(Remarks to the Author)
The manuscript analysizes a dataset of dense crowds and develop some models based on the odd frictions to explain some of the phenomenology observed.

Understanding the dynamics of human crowds is an outstanding scientific challenge with important applications in the field of crowd management, with implications for the design and for the safety of infrastructures and events. The key starting point for these studies is the availability of high-quality (high resolution, high statistics) data. The present study is based on a data collection champaign which took place over a 5 years period in 3 different occasion of the San Fermın festival (Pamplona, Spain). This is a rather unique dataset as high quality recordings of high density crowds, under reproducible yet safe conditions, are rare. I believe the dataset analized is the most outstanding feature of this work.

The manuscript focuses on high density crowds (large number of person per squared meter) under “almost” no flow conditions. Specifically the authors observe the dynamics of the crowd during the filling of a square, before the start of the festival. Under these conditions the authors observe fluctuactions in the magnitude and in the orientation of the velocity of single individuals which correlate over long distances, as the density of the crowd increases. In general the observations and findings are, from a qualitative point of view, not unexpected neither new, similar dynamics have been seen and reported in different conditions but, as mentioned above, the key added value of this work is in the more accurate measurement of the crowd dynamics under reproducible conditions over several years. The manuscript is overall nicely written and the associated video are quite interesting and illustrative.

There are however several points that should be improved in order to make the manuscript more precise, also helping to put the results in a broader perspective.
The manuscript refers to “massive crowds” (e.g. in the title), dense crowds, ultra-dense crowds and dilute-crowds but never define what these terms mean. What is the difference between a massive crowd and a ultra-dense crowd? As the manuscript aims at quantitatively modeling crowds, starting from a precise definition of the observed crowds is important.
The authors justify the relevance of their study in the context of safety of high-density crowding conditions, notably in presence of walls. We are all aware of the unfortunatly rather regular occurrence of accidents with crowds worldwide, therefore I fully agree with the relevance of developing a quantitative understanding of the dynamics of crowds.

The specific crowd studied here is composed by individuals waiting for the festival to start, with the square slowly getting filled from the lateral roads. How is this crowd comparable with more common conditions where dense crowds are actually flowing, or are more confined, or possibly characterized by multidirectional flows? I think it is important that the results from the present study are connected and compared with other crowd conditions. This is important for a broader impact which should go beyond the dynamics in the square of the San Fermin festival.
As already mentioned the dataset analized are rather original and rare, these may help understanding some general aspects of dense crowds. Here the authors first conduct some analysis of the data, presenting some of the observed phenomenology and then discuss at length a model aimed at quantitatively explaining what observed.
The main phenomenological findings are: presence of spatio-temporal heterogeneity (the word intermittency is used in the text, what is its precise meaning here?), non-linear increase in the rms velocity as a function of the density, longer range correlation of velocity directions with respect to magnitude, presence of characteristic oscillation frequencies that depend on the density (Fig. 3f). To explain these finding the authors employ the concept of odd friction.

I have 3 major points I would suggest to the author to consider:
1 – When explaining the observed data it is generally preferable to employ the simplest possible model. I think the authors fail to convince if/why simpler models could not explain what is observed. Why would odd friction be essential? Which features could not be reproduced in terms of even simpler models?
2 – The model introduced can explain only part of the observed phenomenology and only at a rather qualitative level. This is rather surprising given that several free parameters are necessary and yet the agreement with observation seems to be mostly qualitative (e.g. Figs 3a-c and Fig3f). Is this a problem of the model or of the data? How do the authors explain the apparently discontinuos behaviour in Fig. 3f?
3 – The experimental data and figures should be accompanied by an estimate of both statistical as well as systematic error-bars throughout.
In the manuscript a large emphasys is given to the presence of “chiral dynamics”. Looking at the video one remains with the impression that persons arriving from the lateral roads act as a sort of source, producing some kind of two dimensional straining flow. In 2d hydrodynamical straining flow of course one produces positive and negative vorticity (I guess what are dubbed here as “chiral” states). It seems this is precisely what is happening here or is there some fundamental difference? I also do not understand the lengthy discussion on the spontaneous symmetry breaking, in the end the total chirality is precisely observed to remain zero.
Finally, and maybe most important towards a broader impact, what does this model and the observed dynamics teaches us about dense crowds? Can we extrapolate these findings to other types of (e.g. flowing) crowds? Do we have now a model or quantities that can be measured that allow e.g. to provide warnings that the crowd is getting in a dangerous state?

Finally, there are several sentences in the manuscript that I find ambiguous and I would suggest to the authors to clarify them.
- “With this last observation, we are now equipped to answer a well posed question: how do dense crowds spontaneously break the parity symmetry of their dynamics to self-organize into coherent chiral oscillators?” -> As discussed above, I am not sure this is a well posed question. How would this differ from the dynamics of a maybe viscoelastic fluid in 2d?
- “Altogether these measurements indicate that the crowd is a compressible material even in the dense regime.” -> I do have few doubts about the fact that a crowd can be considered as a compressible fluid, but I am not sure from “which” measurements here one should be able to arrive to this conclusion and how is the compressibility of the crowd connected with the mathematical model discussed later on in the manuscript? I cannot immediately see any connection.
- “In the crowd modeling language, the concept of fundamental diagram does not apply to our massive crowds” -> I would suggest the authors to be more precise here. The fundamental diagram is usually associated to the behaviour of the average velocity versus density. First, one can have situations where fluctuations can be rather large with respect to the average, that does not imply that a fundamental diagram does not exist, second, in a situation where the total average velocity is zero, one

could possibly still be able to measure the fundamental diagram by a local analysis.
- “The orientation and speed spectra also imply that the individuals packed in the crowd follow persistent closed trajectories at a noisy speed.” -> I find this sentence not clear, what does closed trajectories at a noisy speed mean? Are we even sure that the trajectories are closed and why should that be the case?
- “The crowd oscillations do not stem from back-and-forth motion” -> This sentence is also not fully clear to me, under large fluctuations imposed by the crowd it is not surprising that there is a sort of circular motion, but in some situation an almost back-and-forth motion maybe present. Maybe the authors want to say that perfectly linear oscillation are rare and non typical?

Line 98 – stationnary.

Version 1:

Reviewer comments:

Referee #1

(Remarks to the Author)
I thank the authors for their efforts to address the points raised in the reports. Overall, especially the clarity of the presentation has very much been improved. The technical points in the reports have mostly been resolved in a satisfactory way.

However, I am still struggling to recommend the manuscript for publication in Nature. Although the empirical part, including the data analysis, is excellent, I do not find the theory part convincing enough.

Considering the title, abstract and section titles it seems that the theory is more important for the authors than the observations. I am aware that this is most likely not true, but the structure of the manuscript very much puts the focus on theory. E.g. the title mentions "prediction" and "modeling", but not "observation" of collective oscillations. Interestingly the latter is very much emphasized in the reply to my report (although the authors appear to have somewhat misunderstood my remark on the novely which I never really questioned).

From the introductory paragraph one can get the impression that the authors try to provide a counter-example to the "dominant paradigm [...] for crowd dynamics" that emphasizes the role of "two-body interactions". Although it makes perfect sense to have a critical look at any paradigm, it puts additional burden on the authors. Alternative approaches that are not perfectly in line with a paradigm require very convincing arguments. It has to clearly substantiated why the paradigm is not applicable and alternatives are needed. Here, in my opinion, the authors do not succeed with the current explanation. Alternatives are not discussed nor are convincing arguments against alternative, maybe more traditional, explanations are provided.

Intuitively, an explanation based on *active* friction forces in an almost stationary crowds is counter-intuitive! While this does not imply that it is not correct, more care in the justification is needed. I can imagine several other effects that could be relevant. E.g. while I agree with the importance of the confinement, it is not appear to be perfect. There are still some boundary flows, especially inflows. One could imagine that this triggers realignment effects in the crowd, e.g. when new spectators arrive. In this realignment, small empty space will be occupied leading to a chain reaction of moving pedestrians. The desire to stay close to friends or family could potentially favor a motion that supports chirality. While I am not claiming that this is a better explanation (or even at explanation at all), the relevance of sterical interactions, fluctuations, social interactions (herding,...), boundary conditions etc. have not been discussed sufficiently.

Overall, I think that a paper that puts the focus on the empirical observations and data analysis could be publishable. The modeling aspects could be discussed in the SI, together with potential alternatives and the reasons for their insufficiency. In any case, the title needs to be changed as "prediction" is actually not discussed and might not even be possible.

Referee #2

(Remarks to the Author)
The modifications made during the revision of the manuscript are important and improve the reading and understanding of the results.
The clarification of the nature of the crowd at the Saint Firmin Festival provides a better context of the situation.
Furthermore, the observation of chiral oscillations at the Love Parade in Duisburg provides a very convincing element for the generalisation of the results.

From my point of view, the manuscript sheds new light on the dynamics of dense crowds, drawing on new and repeated empirical observations as well as meticulously formulated and analysed new modelling, all using a rigorous and precisely detailed methodology.
These results have both wide appeal in the scientific community at large and original results of great value to the specialist community.
For these reasons, I strongly recommend the publication of the manuscript.

Referee #3

(Remarks to the Author)
The authors have satisfactory addressed all my comments.

The theory section has been revised, simplified, and now it aligns more closely with the data. I appreciate the authors' effort to analyse a different scenario (e.g., the Love Parade). Overall, these are impressive dataset, and I hope the authors will make their raw datasets available to allow other researchers to explore this valuable resource from different perspectives.
I support the publication of this work in Nature.

Referee 1

Dear Referee 1,

We thank you for your informed and thorough review of our manuscript. Guided by your questions, suggestions and comments, we set out to further improve our research and better establish the significance and novelty of our main findings.

In particular, using publicly available videos we have shown that at the onset of the Love Parade disaster in 2010, the crowd motion featured the same chiral oscillations as the one we have consistently observed during the opening of the San Fermín festival. In addition, prompted by your comments and that of the two other reviewers, we have improved our theory, we better explain why it is general, and show that it explains all our experimental findings.

To include these additional results, answer your questions, and address your comments, we have significantly revised our manuscitpt, the Methods and SI document. We do hope you will find this revised submission suitable for publication in Nature.

Kind regards,
The authors

We answer in details all your questions and comments below.

A. Summary of the key results:
The authors present empirical results for motion in large crowds. Data obtained from videos taken at a large festival in Pamplona is analyzed based on automated detection of motion of heads. By averaging, the time evolution of density, velocity fluctuations and other relevant quantities are obtained. These quantities are analysed for emergent dynamics. Self-organized collective oscillations are found beyond a critical density. The authors suggest a theoretical explanation for the findings based on the idea that crowds can be described as frictional matter.

Reply: Your summary accurately describes the different steps of our research. Thank you.

B. Originality and significance:
The topic is very interesting and concerns an important open problem in crowd dynamics. However, similar studies have been performed before, e.g. at the Haj in [15] (see also Johansson et al., Advances in Complex Systems 11 (2008)) where the concept of "crowd turbulance" has been introduced. Although this concept can be seen critically, especially the choice of terminology ("turbulence"), similar observations have been made in other works (e.g. Wang et al., Procedia Engineering 84 (2014)). A related concept are "crowd-quakes" (Ma et al., JSTAT (2013) ; Lian et al., Physica A 452). It can be argued that the observations at the Hajj are for a (slowly) moving crowd, but nevertheless a comparison with these findings would be desirable. It is not unreasonable to expect that the relevant mechanisms for self-organization in a standing and a slowly moving crowd are very similar. A static crowd scenario that has been studied in much detail is the Love Parade disaster. Here also a large literature exists.

Reply: First of all, we would like to thank you for your encouraging comments on the topic of our research. We greatly appreciate the effort you made to systematically substantiate your remarks with references to earlier works. We believe this significantly enhances the substance of the scientific discussion.

We fully agree with you on your first point: although the terms "crowd turbulence" and "crowd quakes" have been vastly used in the crowd-modeling literature, their definitions remain elusive. We can however affirm that the flows we observed in the San Fermín Festival, and 2010 Love Parade have very little in common with the turbulent flows of Newtonian fluids. Figure 3 clearly shows that the flows of the crowds we study are periodic in time, in stark contrast with the essential feature of turbulent fluid flows: spatio-temporal chaos. Due to this fundamental difference, we have avoided using the "turbulence" terminologies in our article.

However, regardless of the terminology used to describe dense crowd motion, it is clear that the two essential data bases, and all studies have so far concerned the Haj and the Love Parade disasters. We agree that we should have better contextualized our work with respect to the earlier literature based on these two events. In particular, we have better credited the pioneering work of Johansson *et al.* in our revised manuscript.

We also became aware of the work of Ma *et al.* on the Love Parade "crowd quakes" right after our initial submission. We now explicitly compare our findings to their observations.

Regarding the relevance of our work to different crowds: we have considered your remark very seriously. Using a series of publicly available videos, we have ran our spectral analysis on 2010 Love Parade videos. We show in Fig. 3 that although the San Fermín and Duisburg crowds formed for very different reasons, and in very different contexts, they both feature the same emergent oscillations at high densities. The flows of the Love Parade crowds were not turbulent but periodic and chiral. We believe that the demonstration of this consistent dynamics substantially increases the significance of our results.

We however respectfully disagree with your assessment of the novelty of our findings and their relation to earlier literature. (i) A number of research articles have already reported the emergence of uncontrolled motion in dense crowds. However, to the best of our knowledge, no previous study has ever reported, characterized and explained the spontaneous chiral oscillations of dense crowds based on five consistent experimental datasets. (ii) Revealing the existence of these orientational oscillations is far from being anecdotal. This spontaneous symmetry breaking implies strong constraints on the models able to describe crowd dynamics and rooted in basic physics principles. As discussed in our revised theory section, oscillation in the speed of slowly moving crowds (such as stop-and-go waves) and in the orientation of static crowds cannot be explained by the same physical mechanisms because they involve two different symmetry breaking processes. As far as physics laws are concerned, it is therefore impossible to consider that these two phenomena are identical.

Revision: We now include a discussion of the spectral properties of the 2010 Love Parade dynamics and compare them to our measurements performed on the *Chupinazo* crowd in Fig. 3a-c and new figure 3h. We show that the two crowds feature the same orientational oscillations.

We have also added a full paragraph to stress on the fundamental difference between our chiral oscillations and the stop-and-go oscillations seen in the slowly moving crowd of the Hajj, and in other strongly polarized dense crowds (Lines 144–150).

C. Data & methodology: validity of approach, quality of data, quality of presentation:
The data has been analysed carefully, using state-of-the-art techniques. Potential problems in the detection, e.g. occlusion and other obstructions (Fig.1f), have been reduced by applying machine learning based methods.

Reply: We thank you for your encouraging assessment of our data.

D. Appropriate use of statistics and treatment of uncertainties.
Statistics of the extracted data has appropriately been determined. In Fig.1a one can clearly see large shadow effects that make distinction of heads difficult. How has this problem been addressed?

Reply: We indeed forgot to mention how we dealt with the impact of the shadow when measuring the flows from our 2019 videos.

Revision: We have added a paragraph in Methods to explain how we correct for the sharp change in the image brightness (Lines 327–330).

E. Conclusions: robustness, validity, reliability:
The conclusions presented are based on a single scenario, for which data of 3 different years have been analyzed. The comparison of the 3 years shows that the results are robust, at least for this scenario. However, it is unclear how this generalizes to other settings. It has not been discussed in much detail how general the findings are. The theory presented explains some observations correctly. On the other hand, it becomes clear that something is missing. Fig.3a shows that the peak structure is reproduced, but the behavior outside of the peaks is not described well.

Reply: You have raised two fair and important points.

– Firstly, as detailed above, we have taken into account your comment about the relevance of our results to other settings: (i) We have conducted an addition series of measurements in Pamplona in 2024, (ii) we have analyzed the crowd dynamics after the opening of the San Fermín festival, when security teams change the boundary of the packed crowds, (iii) more importantly we have analyzed series of available videos of the 2010 Love Parade. We believe that the consistency of all our measurements summarized in Fig. 3 provides a convincing answer to your legitimate question about the broad relevance of our findings.

– Secondly, it is true that the theory presented in our first manuscript failed at describing the fat tails of the velocity spectra. Although our goal was to pinpoint the physical origin of the orientational oscillations, we have again taken your comment into account to improve our theory.

A systematic construction and resolution of our crowd-mechanics model allowed us to take into account the role of confinement, and to provide an explanation for the fat tails beyond the value of the oscillation frequency.

Revision: To establish the generality of our findings we report new series of measurements on the *Chupinazo* and Love Parade crowds in Figs. 3 and 4 and comment them in the main text.

We construct a general nonlinear theory of crowd mechanics. We explain it more accurately both in the main text and in a significantly extended SI document. We compare our improved theoretical predictions to our measurements in Fig. 3. The fat tails of the velocity spectra are correctly captured by our model.

I am not fully convinced by the theoretical approach as several points are not considered, as well as alternative theories.

Reply: It was difficult for us to understand the origin of your skepticism, and the alternative theories you had in mind. However, based on all the reports, we decided to better explain and generalize the construction of our mechanical description of crowd motion [equations (1) and (2)]. We also explain why this model is general, and does not rely on uncontrolled assumptions. We stress in the main text that it is not heuristic but strongly constrained by conservation laws, and by the symmetries of the crowd dynamics uncovered by our measurements.

Our approach is very much inspired by the construction of generalized hydrodynamics theories in condensed matter physics. We have made an additional effort to make our reasoning accessible to an audience unfamiliar with this line of research.

Reply: We have completely rewritten the theory section, and now compare our predictions to our measurements in Figs. 3 and 4. We have also added illustrations in Fig. 4 to guide the readers, and help them better understanding the meaning of equations (1)-(3).

At high densities the possible motion is strongly determined by steric restrictions, e.g. due to the body shape. It seems that the theory over-emphasizes the role of friction over the relevance of interactions between the individuals.

Reply: In the bulk of the crowd, the effect of contact interactions between the bodies of the individuals can only play a role in the definition of the mechanical stress tensor and cannot yield any net body force acting on the center of mass of the crowd, in virtue of momentum conservation. The stress tensor therefore contributes to momentum conservation in the form of a gradient term that does not play any role in a mean field description.

However, prompted by your comments, we now explicitly account for the important role of confinement. Steric interactions transmit the contact forces between the wall and the pedestrians. This net force confines the center of mass of the crowd and therefore affects its dynamics. Although the impact of friction is absolutely crucial to account for chiral oscillations, we show that contact interactions play an important role through confinement, even within a mean-field picture.

Revision: The $V(\mathbf{u})$ term in equation (2) results from the contact interactions between the individuals and with the confining walls. Rewriting the theory section, the Methods and SI, we show that these forces conspire with friction to yield an odd mechanical response of dense crowds [equation (3)].

F. Suggested improvements: experiments, data for possible revision:
Why is 0.1 chosen as critical value for correlations (page 3)? Have other values been tested? What is the influence of the choice of this parameter?

Reply: There is nothing special about this value. As shown in figure R1, different criteria give different absolute values for the correlation lengths but their relative variations remain unchanged. This is a standard properties of correlations lengths defined from the decay of correlations functions.

G. References: appropriate credit to previous work?:
A proper discussion of previous related work, e.g. on crowd turbulence and crowd quakes, is missing (see above). There are several related studies in the context of crowd disasters, e.g. the Love Parade disaster. Are these findings compatible with those presented here? Furthermore, there is a vast literature on "synchronization" (e.g. rhythmic applause, Mexican wave,...) that could be interesting to explore. General results for the synchronization of oscillators

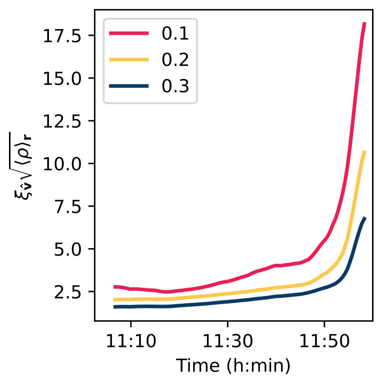

FIG. R1. Orientational correlation length $\xi_{\hat{\mathbf{v}}}$ plotted versus time (Pamplona 2023). Using three different thresholds to define $\xi_{\hat{\mathbf{v}}}$, we find the same evolution. We chose to use the threshold 0.1 that corresponds to the point where the correlation function takes a value comparable to our resolution.

have been obtained that could be useful. See e.g. the (old) review by Boccaletti et al., Phys. Rep. 366.

Reply: As detailed in the answer to your comments about the originality of our work (point B), we have followed your recommendation. We should have better compared our findings to what was discussed in previous works in our initial submission.

We also thank you for suggesting to consider the relevance of synchronization physics. We have not quantified yet the spatial structure of the phase of the crowd oscillations. Therefore the concept of synchronization cannot be applied to our first series of results. But investigating the synchronization of the chiral oscillations would definitely be an interesting question to address in the future. Thank you!

Revision: We have added a number of references to pioneering works on "crowd turbulence" and "crowd quakes" both in the abstract, introduction and in the body of the main text. We now explicitly contrasts the dynamics of the crowds we study with the concept of turbulence, we also show that "crowd quakes" feature chiral oscillations that are markedly different from the speed oscillations of slowly moving polarized crowds. Finally, we stress on the crucial similarities between the San Fermín and Love Parade crowds in the dense regimes in a special paragraph and in Fig. 3.

H. Clarity and context: lucidity of abstract/summary, appropriateness of abstract, introduction and conclusions:

There is a certain redundancy of non-essential information, e.g. in Introduction. The presentation could be more compact. Also pointers to general reviews and books on pedestrian and crowd dynamics would be useful for readers not so familiar with the topic. For me the balance between theory and analysis of empirical data is not convincing. The focus should be much more on the empirical results. Currently the theory has too much weight and its presentation could easily be compactified.

Reply: We thank you for your comments about the structure of the introduction, and the need to add more general references on crowd motion.

Regarding the balance between the presentation of our experimental results and of our theory, given the comments your raised with the other two referees, we found it difficult to streamline more the construction and the discussion of our physical model. We believe that the construction of a physical model of crowd motion rooted in symmetry principles and conservation laws opens a genuinely new line of research in crowd modeling. The technical aspects of our theory are discussed in the Methods and SI, but we believe that our main results (the emergence of odd friction and chiral oscillations at a non-reciprocal phase transition) are deep, and could have implications beyond the specifics of crowd mechanics. We do feel that they deserve a proper discussion in the main text.

Revision: As indicated by the text in blue color, we have completely rewritten our introduction to clarify and better contextualize our research. We have also added a series of references to review articles on crowd dynamics to help readers unfamiliar with this line of work.

To make our theory more accessible to a broad readership, we have rewritten its presentation, and added illustrations in Fig. 4 to give an intuitive picture of our equations (2) and (3).

Minor points concerning the presentation: Considering previous studies mentioned above, some statements in the Abstract appear to be a little exaggerated, e.g. "lack quantitative characterizations of these emergent dynamics". Although it is true that more and better data is needed, it is not correct that no quantitative results exist. Also a statement like "hitherto unpredictable motion" is somewhat misleading. The motion of individuals can also not be predicted by the present approach!

Reply: Thank you for having helped us improving our introduction and abstract.

Revision: We have completely rewritten the abstract and the introduction. Although we believe it is fair to say that we still lack quantitative characterizations of large-scale crowd dynamics (mostly because we lack data), we did our best to avoid any possible overstatement in the presentation of our findings. We hope you will find our revised abstract and introduction clearer and more accurate.

On page 3, line 106, it is emphasized that the fundamental diagram approach does not apply to massive crowds. While this is true, other quantities have been suggested to characterize such crowds quantitatively, e.g. by Zanlungo et al., Transp Res Part C 148, or Cordes et al., PNAS Nexus 3.

Reply: We are not sure to correctly understand your comment. The dimensionless numbers introduced by Zalungo *et al.* and by Cordes *et al.* have a very different status than the so-called fundamental diagram. The fundamental diagram provides a constitutive relation that characterizes a material property. The dimensionless numbers quantify the relative importance of two competing phenomena or of two typical scales and help distinguishing dynamical regimes.

We can however comment on the relevance of the dimensionless numbers introduced by Zanlungo and Cordes, which might partly answer your question. Zanlungo defines a congestion numbers from a second spatial derivative of the velocity field. It is therefore *a priori* unlikely to capture any temporal feature of the flow such as the chiral we focus on. The two dimensionless numbers introduced by Cordes are based on two behavioral hypotheses, and are therefore better suited to test the relevance of heuristic models based on time-to-collision, and on the existence of a social distance above which contact interactions become irrelevant. As pointed out by Referee 2, in the tentative phase diagram sketched in Codes et al article, our crowd would lie in the region where the packed crowd is in a quiescent state (waiting). This shows that this two numbers alone cannot predict the collective behavior of the crowd. Markedly different dynamical states are not distinguished by this set of two numbers.

Revision: We now refer to the work of Cordes *et al.* in the first paragraph of the introduction and in the bulk of the main text.

Recommendation:
The topic is certainly very interesting and highly relevant. However, the authors have not convincingly shown that their results are a real breakthrough in the field. Similar observations have been made earlier under the name of crowd turbulence or crowd quakes. The finding of an orbital-type motion is, to my knowledge, new, but in some sense "a detail". Furthermore it is unclear how the findings presented generalize to other settings, e.g. a typical concert scenario in a stadium. The results certainly deserve publication (after the comments above have been considered), but in a more specialised journal where it reaches the relevant audience more efficiently.

Reply: Your critics and comments have been very helpful to improve our manuscript. It us took some time and efforts to conduct new observations, perform new analysis, construct a general theory and rewrite our manuscript. But it was worth it. We believe that both our new results and our improved manuscript convey much deeper and significant understanding of dense-crowd dynamics.

We hope that you will appreciate: (i) the fundamental difference between our findings and earlier reports of "crowd turbulence" and "crowd quakes", (ii) the identification of an unanticipated collective dynamics in settings as different as the San Fermín festival and the Love Parade at the onset of the 2010 disaster, (iii) the construction of a general theory for confined dense crowds. These three points rely on a pivotal discovery: chiral orientational oscillations can spontaneously emerge in dense crowds. We hope we have convincingly explained why this result is not a mere detail but an essential feature that fundamentally shapes our physical understanding of macroscopic crowd motion.

We thank you again for your informed report and hope you will find our revised manuscript suitable for publication!

The authors.

Referee 2

Conclusions: In my opinion, the conclusions drawn in the manuscript regarding crowd dynamics at the Festival of San Fermìn are robust, valid, and reliable.

Dear Referee 2,

We would like to thank you for your very encouraging report, your comments and suggestions that all helped us clarifying our main findings. We have taken all your remarks into account to improve our manuscript and provide detailed answers to your questions below. In our revised version we include additional data on the Pamplona crowd and show that our findings also apply to the crowd dynamics observed at the onset of the Love Parade disaster in 2010. We have also significantly improved our theory. We do hope that you will find this revised submission suitable for publication in Nature. Thanks again!

Kind regards,
The authors

Suggested improvements:
As mentioned above, I would like to suggest providing a more precise contextualization of the festival environment, including details about the composition of the crowd and the motivations of the participants.
It could be beneficial to contextualize the festival situation before extrapolating these findings to crowd dynamics in general. The authors note in the Methods section that "Before this event, no external guidance dictates the dynamics of the crowd. No acoustic, visual, or mechanical signal coordinates the motion of the crowd." Yet, the context is clearly festive, with the majority of the crowd that seems composed of young men. What are their motivations? They likely aim to celebrate the festival and are probably excited by the event. To what extent does this context influence the observed dynamics? Could they intentionally aim to initiate crowd movement? As far as I know, some experiments conducted in 2013 with up to 600 pedestrians in a 10×10 meter area delimited by borders didn't reveal any oscillatory patterns (see DOI: 10.1093/pnasnexus/pgae120, Appendix A, "Waiting" scenario).

Your remarks and suggestions were particularly valuable. They deserve three separates answers.

– Firstly, following your recommendation we have added a description of the crowd formed at the San Fermín festival in the Methods section (Lines 267–282). As correctly noted in your report, it is mostly composed of young adults. However, the festival attendees are not only locals who know about the tradition of the *Chupinazo*, but also includes a number of foreigners who gather in Pamplona to party during the San Fermín week.

– Secondly, irrespective of the crowd composition, a very legitimate question is whether the dynamics we report is specific to a given crowd or generic. Together with the other two referee reports, your question prompted us to better establish the broad significance of our findings. To do so we performed two additional series of measurements. (i) We have repeated our analysis on the same *Chupinazo* crowd but after the opening of the festival. Unlike before the festival opening, the crowd no longer merely waits but enjoys the music played by the orchestras. (ii) We ran our spectral analysis on surveillance videos of the 2010 Love Parade disaster.

Remarkably, we consistently revealed the emergence of collective chiral oscillations in these two additional situations. We were happily surprised to be able to run these analyses given the poor quality, and short duration, of the Love Parade videos. We do believe that these additional results are a much valuable addition to our work as they ascertain the robustness of our main findings: the emergence of spontaneous chiral oscillation in dense crowds powered by transverse frictional forces.

– Thirdly, we cannot agree more with you on this point: density is not the sole state parameter of a crowd. The behavior reported in Cordes *et al.* is very different from the lively dynamics of the *Chupinazo* crowd. It is in fact similar to the behavior we observe when the city mayor of Pamplona shows up on the city hall balcony prior to the festival opening. As stated in the main text (Lines 70–71), the participants of the *Chupinazo* arrest their motion in response to the visual and acoustic information that signal to opening of the festival. Large amplitude oscillatory motion **can** emerges in dense crowds and lead to disasters. But dense crowds do not *have to* oscillate. Density is not the sole state variable of this polymorphic medium.

2. Another comment pertains to the festival's context, particularly regarding the size of the area. Could we anticipate that the size of the oscillatory patterns depends on the size of the area, or do they possess a characteristic size?

Additionally, is there a critical system size for the emergence of the oscillatory patterns, and does the critical density level (here approximately 4 pedestrian per square meter) depend on the size of the system? These questions are not trivial to answer, but perhaps identifying the most unstable wavelength in the stability analysis or conducting simulations with the proposed crowd model could provide valuable insights for the reader.

Ideally, we would have liked to conduct a series of observations performed in increasing large enclosures. Unfortunately conducting series of measurements on the very same crowds in different geometries is out of reach of any experimental system we are aware of.

We can however partly answer your questions based on our experimental findings. Regarding the values of the correlation lengths, (i) it is clear that the speed fluctuations correlate over distances that are much smaller than the extent of the *plaza Consistorial* (Fig. 2e, inset). We can therefore readily conclude that ξ_{v^2} is an intrinsic property of the crowd. (ii) The correlation of the velocity orientation extends over much larger scales that become comparable to the width of the plaza when the density reaches its maximal value. However, when plotting the variations of $\xi_{\hat{\mathbf{v}}}$ with time in Fig. 2d (inset), we do not observe any saturation. This monotonic increase implies that $\xi_{\hat{\mathbf{v}}}$ cannot be solely set by the distance between the boundaries confining the crowd. In this case $\xi_{\hat{\mathbf{v}}}$ would saturate.

We agree that there could exist a limit to the crowd size, below which the emergent oscillations could be suppressed. Neither our experiments, nor our theory can answer this question. As a matter of fact, our mean-field model is by definition not suited to make any prediction about the typical length scales observed in the crowd dynamics.

3. I couldn't determine whether the stability condition 9 ¡ 'y holds irrespective of $\gamma_{\mathbf{p}}$, or only when $\gamma_{\mathbf{p}}$ is significantly greater than γ. Regarding the model's structure, I would anticipate that $\gamma_{\mathbf{p}}$ influences the dynamics, and stability is likely constrained by this parameter as well. Providing additional information on this aspect could be beneficial for the reader.

Very unfortunately the formatting of your report suffered from symbolic transcription errors, thereby making your question difficult to address.

From our understanding, your question concerns the stability criterion for the onset of oscillations. In our revised manuscript we present a generalization of our initial theory. Taking into account the effect of confinement on the crowd dynamics, we indeed show that the parameter $\gamma_{\mathbf{p}}$ contributes to defining the onset of collective oscillations. We provide a comprehensive discussion of the stability of the quiescent and chiral phases in SI.

4. I would also recommend providing more interpretation of the parameters 'y and 9, as well as the stability condition, in relation to the behavior of pedestrians, particularly in connection with the concept of social and pushing forces commonly used in microscopic pedestrian modelling. Such insights could assist the reader in better understanding the physics underlying the proposed crowd model.

In order to better illustrate the physical meaning of equations (1)-(3) we now illustrate the role of three important terms in Fig. 4.

Your point about the connection to social-force models deserves a separate answer. The core idea of our work is to characterize and explain the dynamics of crowds as active continua. As in all other instances of condensed matter, even the most accurate measurements of the *macroscopic* properties of a crowd cannot be unambiguously related to a unique set of *microscopic* interactions. All interactions and dynamics that obey the same symmetries and conservation laws result in the same physics at the continuum level. It is therefore fundamentally impossible to discriminate different "social force models" that would share the same symmetries based on our findings.

However, our measurements indicate that crowds must support interactions that do not conserve momentum. This macroscopic property translates at all scales and constrains the mathematical modeling of crowds at small scales. In terms of effective (or social) interactions, it means that they cannot be modeled only as reciprocal two-body forces as e.g. the one considered in the first social-force model.

From a different perspective, the core idea of our work is to characterize and explain the dynamics of crowds as active continua. As in all other instances of condensed matter, even the most accurate measurements of the *macroscopic* properties of a crowd cannot be unambiguously related to a unique set of *microscopic* interactions. All interactions and dynamics that obey the same symmetries and conservation laws result in the same physics at the continuum level. It is therefore impossible to discriminate different "social force models" from our findings.

To conclude on a more constructive note, our measurements indicate that crowds must support forces that do not conserve momentum. This macroscopic property translates at all scales. In terms of effective (or social) interactions, it means that they cannot be reciprocal two-body forces. This basic observation constrains their mathematical modeling.

5. I couldn't ascertain how the local density is estimated. If this information was indeed not provided, it should be included for clarity and reproducibility purposes.

We have revised the main text to better assist the readers. They can find all the details about our density measurements in the Methods section (Lines 347–367).

Referee 3

The manuscript analysizes a dataset of dense crowds and develop some models based on the odd frictions to explain some of the phenomenology observed.
Understanding the dynamics of human crowds is an outstanding scientific challenge with important applications in the field of crowd management, with implications for the design and for the safety of infrastructures and events. The key starting point for these studies is the availability of high-quality (high resolution, high statistics) data. The present study is based on a data collection champaign which took place over a 5 years period in 3 different occasion of the San Fermın festival (Pamplona, Spain). This is a rather unique dataset as high quality recordings of high density crowds, under reproducible yet safe conditions, are rare. I believe the dataset analized is the most outstanding feature of this work.

Dear Referee 3,

We would like to thank you for your very useful report that helped us improving both the clarity and the significance of our findings.

In particular, using publicly available videos we now show that at the onset of the Love Parade disaster in 2010, the crowd motion featured the same chiral oscillations as the one we have consistently observed during the opening of the San Fermín festival. We believe that this consistent yet unanticipated result strongly increases the significance of our work. In addition, prompted by your comments, we set out to improve our theory, we better explain why it is generic, and we show that it explains all our experimental observations.

We have significantly revised our manuscript, and SI document to answer your questions, and address your comments. We hope you will find this revised submission suitable for publication.

Kind regards,

The authors

The manuscript focuses on high density crowds (large number of person per squared meter) under “almost” no flow conditions. Specifically the authors observe the dynamics of the crowd during the filling of a square, before the start of the festival. Under these conditions the authors observe fluctuactions in the magnitude and in the orientation of the velocity of single individuals which correlate over long distances, as the density of the crowd increases. In general the observations and findings are, from a qualitative point of view, not unexpected neither new, similar dynamics have been seen and reported in different conditions but, as mentioned above, the key added value of this work is in the more accurate measurement of the crowd dynamics under reproducible conditions over several years. The manuscript is overall nicely written and the associated video are quite interesting and illustrative.

Reply: Thank you for your very enthusiastic comments about the quality of the data that we set out to collect and analyze!

We were sorry to read that you have not been surprised by our observations. We cannot argue about your personal impression, but we were confused by your comment about the novelty of our findings. It seems to us that saying that our results are not new and that “similar dynamics have been seen and reported in different conditions” is incorrect. We are not aware of any experimental, numerical or theoretical study of dense crowd which has ever reported one of our three essential results recalled below:
(i) Dense crowds can support collective chiral oscillations.
(ii) The handedness of spontaneous orbital motion can correlate over system spanning scales in dense crowds.
(iii) Dense confined crowds can be described as frictional matter featuring an emergent odd response and a non-reciprocal phase transition towards spontaneous oscillations.

We believe that your initial assessment reflected an unclear presentation of our results. For this reason, we have done our best to clarify the presentation of our results and to better explain the significance and novelty of our main experimental and theoretical findings.

We do hope that your will appreciate the novelty of our work when reading our revised manuscript!

There are however several points that should be improved in order to make the manuscript more precise, also helping to put the results in a broader perspective. The manuscript refers to "massive crowds" (e.g. in the title), dense crowds, ultra-dense crowds and dilute-crowds but never define what these terms mean. What is the difference between a massive crowd and a ultra-dense crowd?

Reply: Thank you for pointing out this inconsistency in the wording of our initial submission.

Revision: In our revised manuscript, we now consistently refer to "dense crowds" throughout the main text, Methods and SI document.

As the manuscript aims at quantitatively modeling crowds, starting from a precise definition of the observed crowds is important. The authors justify the relevance of their study in the context of safety of high-density crowding conditions, notably in presence of walls. We are all aware of the unfortunatly rather regular occurrence of accidents with crowds worldwide, therefore I fully agree with the relevance of developing a quantitative understanding of the dynamics of crowds.
The specific crowd studied here is composed by individuals waiting for the festival to start, with the square slowly getting filled from the lateral roads. How is this crowd comparable with more common conditions where dense crowds are actually flowing, or are more confined, or possibly characterized by multidirectional flows? I think it is important that the results from the present study are connected and compared with other crowd conditions. This is important for a broader impact which should go beyond the dynamics in the square of the San Fermin festival.

Reply: We thank you for your suggestion. Our results have indeed no reason to apply to all possible settings such as crowds in motion, multi-directional flows, guided crowds, or crowds following prescribed trajectories.

In order to better establish the broad impact of our results we needed to confirm that our findings apply to different types of crowds. We did so.

Revision: Firstly, we have used publicly available videos of the 2010 Love Parade disaster to show that the so-called crowd quakes consistently reported in the literature are not turbulent but periodic. We show in Fig. 2 that their dynamics mirror the *Chupinazo* crowd's. In addition, we analyzed the San Fermín crowd after the opening of the festival, when the packed attendees celebrate and listen to music played by orchestras. Figure 3 compares the three types of crowd and show that their spectral properties are identical.

Secondly, following your suggestion we are now more specific about the type of crowds we aim at describing: dense confined crowds.

Lastly, we have also added a paragraph in the main text (Lines 144–150), where we distinguish our findings from observations made in dense walking crowds where "stop-and-go" waves have been consistently reported, and in heavy-metal concerts (where the attendees intentionally form specific patterns such as large vortices, or the "wall of death").

As already mentioned the dataset analized are rather original and rare, these may help understanding some general aspects of dense crowds. Here the authors first conduct some analysis of the data, presenting some of the observed phenomenology and then discuss at length a model aimed at quantitatively explaining what observed. The main phenomenological findings are: presence of spatio-temporal heterogeneity (the word intermittency is used in the text, what is its precise meaning here?), non-linear increase in the rms velocity as a function of the density, longer range correlation of velocity directions with respect to magnitude, presence of characteristic oscillation frequencies that depend on the density (Fig. 3f). To explain these finding the authors employ the concept of odd friction.

Reply: You have correctly summarized most of our results, and we agree that the term "intermitent" might have led to some confusion.

Revision: We have removed the term "intermitent" to avoid any unwanted analogy with genuine turbulent flows.

We have also generalized and improved our theory. We now show how active friction and confinement result in odd elastic response that sustains chiral oscillatory flows in dense crowds.

I have 3 major points I would suggest to the author to consider: 1 – When explaining the observed data it is generally preferable to employ the simplest possible model. I think the authors fail to convince if/why simpler models could not explain what is observed. Why would odd friction be essential? Which features could not be reproduced in terms of even simpler models?

Reply: We do agree with you. Using a minimal model to account for experimental observations guarantees the robustness of the explanations.

Regarding the role of friction: there is absolutely no doubt that it is essential to explain crowd motion. Pedestrians move only in response to frictional forces on the ground. However, regarding the odd symmetry of the dynamics, we stress that it is not an input of our model but an emergent property. It results from the nonlinear interplay between friction, confinement and, or, inertia.

The emergence of an odd response from the coupled dynamics of the velocity ($\mathbf{v}$) and frictional degrees of freedom ($\mathbf{p}$) is in a one-to-one correspondence with the fact that the velocity follows periodic orbits, while keeping its norm constant. This is typically what odd material parameters yield.

We now explain why equations (1) and (2) provide a minimal model constrained by symmetries. However, in principle, and as stated in the main text, these equations could include a number of non-linearities. In SI, we perform a systematic inspection of all possible models up to third order in non-linearities. We find that observing (i) orientational oscillations at constant speed and (ii) a spontaneous breaking of the chiral symmetry of the trajectories is possible if and only if $\alpha \neq 0$ in equation (2). The role of the other nonlinearities are of lesser importance, but we discuss them systematically in SI.

Revision: Prompted by your report we have generalized our mathematical model and significantly revised the theory section.

Firstly, we explain why equations (1) and (2) provide a general model of confined dense crowds from symmetry considerations (paragraph starting at Line 207).

Secondly, we now carefully account for the effect of confinement, and show that it yields an even better agreement between our minimal model and our measurements (see Fig. 3).

2 – The model introduced can explain only part of the observed phenomenology and only at a rather qualitative level. This is rather surprising given that several free parameters are necessary and yet the agreement with observation seems to be mostly qualitative (e.g. Figs 3a-c and Fig3f). Is this a problem of the model or of the data? How do the authors explain the apparently discontinuos behaviour in Fig. 3f?

Reply: You are absolutely correct, our first minimal model captured the emergence of spontaneous chiral oscillations, but could not explain the discontinuity of the oscillation frequency, and the fat tails of the power spectra. Our improved theory, which includes the effect of confinement, now explains both phenomena. It is always beneficial to be challenged. Thank you!

Revision: We present our improved theory on page 5 of the manuscript and detail it in Methods and SI. We compare our predictions to our measurements in Fig. 3. The agreement is significantly improved as discussed in the main text.

3 – The experimental data and figures should be accompanied by an estimate of both statistical as well as systematic error-bars throughout.

Revision: We have added error bars, and, either estimates or the accuracy of our measurements in all figures and/or figure captions. When the concept of statistical error is irrelevant (when we plot the statistics of an observable) we only provide the measurement error (*e.g.*, Fig 2a).

In the manuscript a large emphasys is given to the presence of "chiral dynamics". Looking at the video one remains with the impression that persons arriving from the lateral roads act as a sort of source, producing some kind of two dimensional straining flow. In 2d hydrodynamical straining flow of course one produces positive and negative vorticity (I guess what are dubbed here as "chiral" states). It seems this is precisely what is happening here or is there some fundamental difference?

Reply: Thank you for sharing your impressions about our videos. Your observations are certainly correct but they cannot account for the dynamics characterized by our measurements.

The flows you describe would result in displacements correlated over large scales, and not in localized orbital motion (Fig 3d). They could not explain the period of the orientational dynamics either. The type of flows you suggest could only explain the period of the observed oscillations if the "mass injection" from the lateral streets was periodic itself, it would then result in oscillations in the flow speed as well, which we do not observe.

I also do not understand the lengthy discussion on the spontaneous symmetry breaking, in the end the total chirality is precisely observed to remain zero.

Reply: What we were trying to say is that there exists no external or internal factor leading to a global symmetry breaking. All the orbits followed by the festival attendees do not have the same handedness. Or equivalently the sign of the spin field is not *a priori* prescribed. In addition, it can change in the course of the stochastic dynamics of the crowds. These observations, and the equal probability of the two spin values, then imply that the parity symmetry of the oscillatory dynamics is spontaneously broken locally, and restored dynamically through fluctuations as you pointed it out.

Revision: We have revised this part of the main text as well text to clarify our explanation (Line 180).

Finally, and maybe most important towards a broader impact, what does this model and the observed dynamics teaches us about dense crowds? Can we extrapolate these findings to other types of (e.g. flowing) crowds? Do we have now a model or quantities that can be measured that allow e.g. to provide warnings that the crowd is getting in a dangerous state?

Reply: This is a fair and important question. We believe we have partly answer it above. In short, comparing our findings to new data that we extracted from the 2010 Love Parade disaster videos, we now show that the emergence of chiral oscillations in dense crowd (i) is not specific to the San Fermín crowd, (ii) is not the result of any *a priori* information about the dynamics experienced by the festival attendees during previous events. (iii) The oscillations result from a non-equilibrium (non-reciprocal) phase transition.

Revision: We now make it clear that our results are not specific to the model crowd of the san Fermín festival (Addition of a new paragraph starting Line 126).

We also explicitly argue that measuring the crowd-velocity spectrum in real time and using raw videos could provide a very effective tool to signal the emergence of uncontrolled oscillatory motion before the amplitude of the displacements becomes large and dangerous (see comparisons with the Love Parade data in Fig. 3, and paragraph below Line 150).

Finally, there are several sentences in the manuscript that I find ambiguous and I would suggest to the authors to clarify them. - “With this last observation, we are now equipped to answer a well posed question: how do dense crowds spontaneously break the parity symmetry of their dynamics to self-organize into coherent chiral oscillators?” -¿ As discussed above, I am not sure this is a well posed question. How would this differ from the dynamics of a maybe viscoelastic fluid in 2d?

Revision: We have clarified this sentence which now reads ”how do dense crowds self-organize into coherent chiral oscillators? ”. Note that we explain in the SI why this dynamics cannot be explained as the response of a viscoelastic medium. They would indeed feature both orientational and speed fluctuations. Only transverse couplings between the frictional force and the flow can account for the observed chiral oscillations.

- “Altogether these measurements indicate that the crowd is a compressible material even in the dense regime.” -¿ I do have few doubts about the fact that a crowd can be considered as a compressible fluid, but I am not sure from “which” measurements here one should be able to arrive to this conclusion and how is the compressibility of the crowd connected with the mathematical model discussed later on in the manuscript? I cannot immediately see any connection.

Reply: The reasoning about the crowd impressibility was indeed not trivial and would have deserved a longer discussion. This was a side comment. As it was a possible source of distraction, we removed this sentence from our manuscript.

- “In the crowd modeling language, the concept of fundamental diagram does not apply to our massive crowds” -¿ I would suggest the authors to be more precise here. The fundamental diagram is usually associated to the behaviour of the average velocity versus density. First, one can have situations where fluctuations can be rather large with respect to the average, that does not imply that a fundamental diagram does not exist, second, in a situation where the total average velocity is zero, one could possibly still be able to measure the fundamental diagram by a local analysis.

Reply: We are not sure to correctly follow your reasoning. Your suggestion seems to be strictly equivalent to the analysis we conduct to produce Extended Data Fig. 2. Our local analysis does not support the existence of a one-to-one correspondence between the speed and density of the crowd. The constitutive relation of this material is of a different nature. We hope that the presentation our our revised manuscript makes it clear that the constitutive relation defined by equation (2) correctly accounts for all our experimental findings.

- “The orientation and speed spectra also imply that the individuals packed in the crowd follow persistent closed trajectories at a noisy speed.” -¿ I find this sentence not clear, what does closed trajectories at a noisy speed mean? Are we even sure that the trajectories are closed and why should that be the case?

Reply: We meant that the trajectories are composed of sequences of orbital motion, and that the magnitude of the velocity (the speed) of the individuals is not constant but fluctuates around a mean value without oscillating.

The Eulerian field oscillates in time at every point in space. Furthermore, the average velocity is vanishingly small. This is the reason why the Lagrangian trajectories have to form orbits.

Revision: In order to avoid any possible confusion, we have clarified our description and now refer to orbital trajectories. ”The attendees follow orbital trajectories” when referring to the dynamics shown in Fig. 3d.

- “The crowd oscillations do not stem from back-and-forth motion” -¿ This sentence is also not fully clear to me, under large fluctuations imposed by the crowd it is not surprising that there is a sort of circular motion, but in some situation an almost back-and-forth motion maybe present. Maybe the authors want to say that perfectly linear oscillation are rare and non typical?

Reply: We would like to stress that the circular trajectories that we describe do not reflect the advection of people by macroscopic vortices. In agreement with your observation, they do not reflect the (possibly imperfect) back and forth swaying motion of the individuals either. As exemplified in Fig. 3g. the Lagrangian trajectories of the festival attendees are composed of series of orbital trajectories whose handedness correlates over macroscopic scales and persists in time. To the best of our knowledge, this type of dynamics has never been reported (neither in any macroscopic passive material, nor in earlier observations of human crowds). One of our main goals was to explain the origin of this spontaneous dynamics.

Revision: We have clarified and simplified the corresponding explanation in the main text, see Line 208.

Line 98 – stationnary.

Reply: Thank you we have corrected this typo.

Response to the referee reports

Referee 1:
Following your instructions and guided by the comments made by Referee 1 we have reversed our abstract and introduction to better contextualise our research and nuance the benefit of opting for a continuum description of crowd dynamics.

Referee 3:
We have uploaded all the data and simulation codes that support the Figures and Extended data Figures on a public repository (Zenodo), and would be happy to share more data upon reasonable request. We are however not keen on sharing our raw dataset in extenso via a public repository, for at least two reasons. Firstly, we provide all the information needed to reproduce our measurements. The « Chupinazo » is an event that repeats itself every year at the same date and location, and we provide all the information

needed to independently perform the same type of measurement as we do (location of the cameras, type of cameras, image analysis and data processing algorithm). We therefore believe that there is no issue concerning the reproducibility of our measurements. Secondly, our raw data consist of images of people, so we are concerned that making these data publicly available could raise ethical concerns.