Creation of an isolated turbulent blob fed by vortex rings

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Turbulence is hard to control. Many experimental methods have been developed to generate this elusive state of matter, leading to fundamental insights into its statistical and structural features as well as its onset. In all cases, however, the material boundaries of the experimental apparatus pose a challenge for understanding what the turbulence has been fed and how it would freely evolve. Here we build and control a confined state of turbulence using elemental building blocks—vortex rings. We create a stationary and isolated blob of turbulence in a quiescent environment, initiated and sustained solely by vortex rings. We assemble a full picture of its three-dimensional structure, onset, energy budget and tunability. The incoming vortex rings can be endowed with conserved quantities, such as helicity, which can then be controllably transferred to the turbulent state. Our one-eddy-at-a-time approach opens the possibility for sculpting turbulent flows much as a state of matter, placing the turbulent blob at the targeted position, localizing it and ultimately harnessing it.

Vorticity, which measures the local rotation rate of a fluid, is the building block of flow. In its absence, any fine structure in an incompressible flow decays rapidly with distance from material boundaries. Conversely, injection of vorticity can power complex bulk flows, the quintessential example being the iconic multi-scale liveliness of turbulence. Canonical methods of generating turbulence rely on the spontaneous shedding of vorticity from boundaries, be it of pipes, grids or spinning plates. This makes it hard to control, or have detailed knowledge of, the fabric of the injected vorticity. It also often couples the turbulence to boundaries, posing a challenge to study its unconstrained evolution. Yet, our most basic models of turbulence are cast in terms of vorticity alone, with no reference to walls.

Knowing the structure of the vorticity that feeds turbulence is fundamental to a full understanding of turbulence because it determines the inviscid invariants including the amount of energy, helicity, linear impulse and angular impulse that are injected into the turbulence. The balance of the latter two invariants, for example, might lead to different types of turbulence in the large scales, and has been proposed to rule the decay of turbulence. To make it possible to address these fundamental questions, we set out to build and sustain an isolated region of turbulence far away from boundaries, while controlling the injection of inviscid conserved quantities and fully observing its free evolution.

Vortex loops are a natural candidate to this end. A vortex ring is readily generated by impulsively drawing water through an orifice in a tank (Fig. 1b). Seeding the water with bubbles reveals the coherent motion of the ring as it travels across the tank, carrying its ‘atmosphere’ as it propagates (Fig. 1c). Such a ring can, in an ideal fluid, travel infinitely far away from the boundaries. In real fluids, vortex rings eventually decay via viscous processes, or break down due to instabilities. Nonetheless, they coherently carry their vorticity, and associated inviscid invariants, far from the boundaries that gave rise to them.

We set out to combine vortex loops like LEGO blocks, firing them together to ‘print’ a stationary region of turbulence in the centre of our tank (Fig. 1a). As demonstrated in iconic vortex collision experiments, recently revisited as a minimal means to understand the inertial cascade in real space, two vortex rings fired together...
In this new state, vorticity is confined, and evenly distributed within an approximately spherical region (Supplementary Video 10). The flow inside the blob is in stark contrast to its surroundings, which remain relatively quiescent. The blob is sustained as long as the vortex rings are injected. Both the energy and enstrophy averaged over the measured plane indicate the comparative steadiness of the state (Fig. 2h) with weak dependence on the periodic forcing.

Figure 3a shows a Reynolds decomposition of this complex flow into mean and fluctuating components:
\[ U_i = \langle U_i \rangle + u_i. \]

The blue cloud represents the average energy associated with the fluctuations and occupies the central region alone, whereas the yellow clouds represent the mean flow energy, associated with the paths along which the vortex rings are fed. We find that the flow inside the blob is dominated by fluctuations \( \left( \frac{\langle u^2 \rangle}{\langle U \rangle} \right) \approx 10^{1.5-103} \) whereas the flow outside the blob is dominated by coherent flow (Supplementary Videos 5–7). Furthermore, the velocity fluctuations inside the blob are only weakly dependent on the forcing phase, whereas the coherent flow outside the blob is phase dependent, reflecting the laminar motion of the vortex rings. The temporally and radially averaged profiles of both the fluctuating energy and enstrophy are approximately constant up to a radius \( R_{\text{blob}} \) (Supplementary Section VB) but decay rapidly for \( r > R_{\text{blob}} \) approximately as \( r^{-4} \). The local dissipation rate \( c_s(r) = 2\nu \langle s_{ij} s_{ij} \rangle \) also possesses the same radial profile as the energy and enstrophy (Fig. 3b), where \( s_{ij} = (\partial_i u_j + \partial_j u_i)/2 \).

To investigate the character of the flow inside the blob, we compute the fluctuating energy spectrum and the second-order
structure function. PIV measurements are inherently limited at small scales by image resolution and at large scales by the finite field of view. To span the full range of scales in our turbulent flow, we performed two-dimensional (2D) PIV measurements at three levels of magnification (Fig. 3d; spatial resolutions $\Delta_x$ of 0.5, 1.3, 2.4 mm = 2.4$\eta$, 6.2$\eta$, 11.4$\eta$, where $\eta$ is a Kolmogorov length scale) and stitched the results together by taking into account the spectral leakage and low-pass filtering effects of PIV. With 3D PTV, we measure a one-dimensional (1D) energy spectrum on the slice that cuts the middle of the turbulent blob with a spatial resolution of $\Delta_x = 3.0 \text{ mm} = 14.4 \eta$. In addition, the resulting four-dimensional (4D) velocity field affords a direct computation of a 3D energy spectrum without the assumption of isotropy (Supplementary Section VIIIH). The resulting 1D energy spectrum $E_1(k_i)$ and the second-order structure function $D_2$, of the fluctuating component of the flow are shown in Fig. 3e,f. Here $k_i$ is a component of a wavenumber vector in the direction that the Fourier transform is performed. Our measurements at the three levels of magnification agree where their ranges of validity overlap. The rescaled spectrum is in agreement with the universal curve obtained by grid turbulence and turbulent boundary layer experiments. Similarly, the second-order longitudinal structure function when rescaled by the $2/3$ power law in the inertial sub-range is consistent with that of homogeneous isotropic turbulence.

Our spectra and structure function support the notion that the flow inside the blob is turbulent and therefore that its statistical properties can be captured by a dissipation rate $\epsilon_0$ and an integral scale $L$ (refs. 36, 37), together with the fluid viscosity $\nu$. The value of $\epsilon_0$ is notoriously challenging to measure. It can be inferred from the local strain rate measurements, from fitting the measured spectrum to the universal curve or by fitting the peak value in the scaled second-order structure function. As discussed in Supplementary Section VIIIB, we find that all three methods are in agreement when computed on our
The smallest (Kolmogorov) length scale of the turbulent blob \( \ell_\text{blob} \) is determined by the largest scale in the incoming vortex rings. This suggests that both the blob radius and integral length scale are to be close to that of the blob diameter \( 2b\). Data presented as mean ± s.e.m. (n = 12). d. Planes display the measurement regions of 2D PIV (i = 1, 2) performed at three levels of magnification. e. Turbulence length scales with respect to the relevant geometries (blob radius \( R_{\text{blob}} \), ring radius \( R_{\text{ring}} \), and core diameter \( a \)). f. Rescaled 1D spectra computed in the homogeneous region (\( r < R_{\text{blob}} \)). Here, \( \epsilon_0 = 6.0 \times 10^4 \text{ mm}^2 \text{ s}^{-2} \), \( \nu = 1,004 \times \text{ mm}^2 \text{ s}^{-2} \), and Taylor Reynolds number, \( \text{Re}_\text{T} = 200 \). \( \lambda \) is a Taylor microscale. The grey master curve is taken from ref. [9] (\( \text{Re}_\text{T} = 600 \)) as a reference. \( \epsilon_0 \) is a component of a wavenumber vector in the direction that the Fourier transform is performed. The attenuated signal due to PIV is shown by hollow data points. g. Rescaled second-order structure functions of the same data as in f shown with a reference curve from ref. [9] (\( \text{Re}_\text{T} = 600 \)). In f and g, the turbulent length scales and relevant geometries in e are shown as vertical lines.

Because the flow is at dynamical equilibrium, the dissipated power must match the power injected by the vortex rings. If we neglect any residual dissipation due to the mean flow, the energy balance is

\[
4\pi \nu \int \epsilon(r)^2 \, dr \approx 8\epsilon_0 f
\]

where \( \epsilon(r) = \epsilon_0 \) if \( r \leq R_{\text{blob}} \) and \( \epsilon(r) = (R_{\text{blob}}/r)^4 \) otherwise. \( K_{\text{ring}} \) is the kinetic energy inside the vortex atmosphere of any one of the incoming vortices.

When integrated over all space, the left-hand side evaluates to \( 16/3 \pi \epsilon_0 R_{\text{blob}}^3 \) whereas if integrated up to \( R_{\text{blob}} \) we have \( 4/3 \pi \epsilon_0 R_{\text{blob}}^3 \). The right-hand side requires knowledge of \( K_{\text{ring}} \). When there is a vortex ring in a flow, the energy over all space \( \kappa \) is generally the sum of the energy inside the vortex atmosphere \( K_{\text{ring}} \) and the energy of the added mass associated with the potential flow that surrounds the atmosphere \( K_{\text{blob}} \). \( K_{\text{ring}} \) can be further decomposed into the translational kinetic energy of the vortex atmosphere \( K_{\text{rec}} = 4/3 \pi \epsilon_0^{3/2} R_{\text{ring}}^2 \) and the energy associated with the rotational motion within the vortex atmosphere \( K_{\text{int}} \). While the exact partitioning varies by the vortex model, the variation for \( K_{\text{ring}} \) is small (<3.3%) for realistic vortex ring models. We directly measured median-filtered, spatio-temporally resolved velocity fields. The corresponding value of the Kolmogorov length \( \eta = (\nu^3/\epsilon_0)^{1/4} \) is shown in Fig. 3e. A measurement of the turbulent r.m.s. velocity \( \sigma' = \sqrt{\langle (u_i - 2b u_i) \rangle} \) in turn provides the estimate of the integral length scale \( \ell = \sigma' \| \ell_0 \).

How are the properties of this turbulent blob controlled by the incoming vortex rings? As shown in Fig. 3e, we find the value of the integral length scale to be close to that of the blob diameter \( 2R_{\text{blob}} \) suggesting that both the blob radius and integral length scales are determined by the largest scale in the incoming vortex rings. This observation is supported by repetitions of our experiment in which we varied the frequency of injection of the incoming vortex rings and found no change in either \( \ell \) or \( R_{\text{blob}} \). A repetition of our experiment in which the incoming vortex ring radius was halved instead resulted in a halving of both \( \ell \) or \( R_{\text{blob}} \) (Supplementary Section XIA).

The smallest (Kolmogorov) length scale of the turbulent blob \( \eta \) (Fig. 3e) has by contrast little relation to the vortex ring radius and is instead strongly affected by the incoming vortex ring energy and frequency of injection. This is consistent with the notion that, at the smallest length scales, turbulence ‘forgets’ about the large-scale forcing that gave rise to it and the velocity field depends only on the energy flux \( \epsilon_0 \) and viscosity \( \nu \). We thus turn our attention to the balance of energy in our system.
the energy of our vortex rings and found $K_{\text{ring}} = (2.0 \pm 0.4)K_{\text{recoc}}$, similar to the result of 23/14$K_{\text{recoc}} = 1.6K_{\text{recoc}}$ for Hill’s spherical vortex (Supplementary Section III).

Figure 3c compares the measured dissipated versus injected power for a collection of blobs created by altering the ring size, speed and frequency of injection. The dissipated power scales linearly with the injected power, with a slope of approximately 1. A more granular account, for example, including only the energy contained within the vortex ring atmosphere and computing $f_c$, only within $R_{\text{blobs}}$ yields a linear relationship with lower proportionality constants: 1 (total energy), total turbulent dissipation), 0.68 (energy within the incoming vortex ring atmospheres), turbulent dissipation within a sphere of radius $R_{\text{ring}}$) and 0.33 (energy within the incoming vortex ring atmospheres, turbulent dissipation within a sphere of radius $R_{\text{ring}}$).

Crucially, increasing the velocity or frequency of injection increases the rate of energy dissipation while keeping the integral length scale fixed, thereby increasing the separation of scales $L/\eta$. Thus, the ring radius and energy injection provide independent control knobs for producing turbulence of a desired intensity localized to a given region.

The picture is in stark contrast to the single-collision experiment (Fig. 2a) in which vortices come in, reconnect and go out. At these low forcing frequencies, the conversion from coherent vortex motion to turbulence is far less efficient. Even though in practice reconnections trigger energy loss within the outgoing vortices, in the limit of a single coherent collision with large separation of scales, the fraction of advected energy can be in principle 100%.

What governs the transition to a blob state? The most basic criterion is suggested by geometry: the outgoing rings will collide with the incoming rings for $f > V_{\text{ring}}/R_{\text{ring}}$. A visualization of coherent vorticity in our flow using the Q criterion supports this hypothesis (Supplementary Video 12). A completely different conceptual approach is to seek to ‘match’ the incoming vortex ‘eddies’ to the turbulent state. A central idea in a turbulent cascade is that energy from each scale is transported to the next in a time $\tau_c = (\epsilon^2/\epsilon_0)^{1/3}$. If we demand that the time between incoming vortices $1/f$ match the time scale for the largest eddy to transfer energy down the cascade, we have $1/f > \tau_c$. For our fully developed turbulent blob, we have $\ell \propto R_{\text{ring}}$ (Fig. 4a; $\alpha_0 = 2.17 \pm 0.13$) and $\epsilon_0 \propto V_{\text{ring}}^2$ (Fig. 4b; $\alpha_1 = 0.35 \pm 0.02$) with proportionality constants determined in experiment. We then obtain a criterion for transition; $f_c = (\alpha_1/\alpha_0)V_{\text{ring}}/R_{\text{ring}}$ with the proportionality constant determined by the independent measurements of $\ell(R_{\text{ring}})$ and $\epsilon_0(V_{\text{ring}})$ in the fully developed turbulent state.

Figure 4e shows the time-averaged enstrophy field for experiments in which we varied both $f$ and $V_{\text{ring}}/R_{\text{ring}}$. The transitional range predicted by matching vortex arrival intervals with the largest eddy turnover time is shown by the blue band for comparison. The relationship between $f_c$...
and $V_{\text{ring}}/R_{\text{ring}}$, consistent with predictions, is qualitatively visible from the change in shape as the frequency is increased. A second criterion to classify whether a given flow is in a blob state is to compute the enstrophy flux through a sphere that encloses the blob (Fig. 4c). For barotropic incompressible fluids, the integrated enstrophy flux is given by

$$
\Phi(t) = \int \Omega^2 U_i n_i dS,
$$

where $\Omega = \epsilon_{ijk} \partial_j U_k$ is the vorticity. Here $n_i$ is the unit exterior normal to the surface $\partial V$, $dS$ is the differential surface element, and $\epsilon_{ijk}$ is the Levi-Civita symbol. The phase-averaged (integrated) flux $\Phi_{\text{avg}}$ is shown in Fig. 4c for an experiment with $f < f_c$ (red) and one with $f > f_c$ (blue). The red curve shows a trough (inflow > outflow), followed by a crest (inflow < outflow) as the secondary rings transport enstrophy away from the considered volume. The blue curve, by contrast, shows little to no outflow (Supplementary Video 8). As $f$ is increased for a given $V_{\text{ring}}/R_{\text{ring}}$, the escaping enstrophy per cycle, $Z_o$, (Fig. 4c, green region) decreases smoothly as the frequency is increased (Fig. 4d). This corresponds to the suppression of coherent reconnections and development of turbulence. Placing a threshold ($<5\%$ relative to the values at $f = 1\, \text{Hz}$) on the escaping enstrophy reveals that the transitional frequency depends on $V_{\text{ring}}/R_{\text{ring}}$ in a linear fashion (Fig. 4e, orange band). The upper limit of the orange band in Fig. 4e lies within $10$–$20\%$ of the predicted transition frequency.

For $f > f_c$, the energy and enstrophy are completely transferred to the blob, in sharp contrast to the single-shot experiment ($f < f_c$), in which neither are left behind nor in fact penetrate the central region. By contrast, the mass associated with the vortex atmospheres must flow in and out in equal amounts and cannot be left behind (Supplementary Section XA). We find it interesting that the blob state can occur in the first place given this fact. Our work raises the question of whether vortex ring trains are in some sense optimally suited to confining and ‘feeding’ turbulence. What types of flow ‘input’ lead to maximally localized blob states versus delocalized states in which the necessary outward advection destabilizes confinement?

Finally, we explore the tunability of our turbulent blob through control of the vortex rings. The ring radius $R_{\text{ring}}$ tunes the integral scale $\mathcal{L}$ and the blob radius $R_{\text{blob}}$. Meanwhile, the energy balance sets the smallest scale of turbulence (the Kolmogorov scale $\eta$) as it leads to $\epsilon_0 = \alpha_0^{\eta/3} f \approx \alpha_0^{R_{\text{ring}}/3} f R_{\text{ring}}^{1/3}$. Hence, the separation of scales is given by $\mathcal{L}/\eta \approx (R_{\text{ring}}/V)^{1/4} (R_{\text{ring}}/V_{\text{ring}})^{1/4}$, consistent with the usual relation $\mathcal{L}/\eta \approx Re_3^{3/4} \approx (\nu'\mathcal{L}/V)^{3/4}$ for general turbulence. Notice that it is expressed solely by the variables of the injecting vortex rings and thus can be completely controlled by tuning their properties.

Can our approach to building a turbulent blob be harnessed to endow the turbulence with additional properties? Beyond energy, natural candidates include the inviscid invariants of impulse, angular impulse and helicity. Colliding these helical rings can in turn produce blobs with finite helicity (see Supplementary Section XIB for details). Figure 5 shows measurements of the total helicity in a blob created by colliding helical vortex loops in combinations that inject a total helicity of $+8\mathcal{L}/\eta$ and $-8\mathcal{L}/\eta$ and $0\mathcal{L}/\eta$, while injecting zero angular impulse and zero linear impulse. Although the vorticity field is not completely resolved (Supplementary Sections IIIIC and XIB), clearly the answer is affirmative.

We have discovered that a collection of vortex rings periodically fired together leads to a self-confining turbulent blob. This bottom-up approach to turbulence provides unique design principles to position, localize and control turbulence as a state of flow. In the canonical picture of the Richardson cascade, injection and dissipation go hand in hand at dynamical equilibrium. Nevertheless, their connection often remains elusive owing to the uncontrolled injection and evolution of vortical structures. The use of coherent, controllable vortex rings overcomes this issue, enabling us to inject fully controlled arbitrary ratios of inviscid conserved quantities. Enabled by the self-confinement effect we discovered, our experiment provides a unique control of injection and dissipation in turbulence. The turbulent blob, which can be measured in its entirety and is free to evolve in isolation, offers a playground for fundamental studies on inhomogeneous turbulence such as the decay of turbulence without interference from boundaries, the response of turbulence to a periodic drive and the role of inviscid invariants such as helicity and angular impulse in turbulence. The steadiness of the turbulent blob makes it an interesting alternative to boundary layers to assess transfer at the turbulent/non-turbulent interface. Our work demonstrates how turbulence can be treated as a state of matter that can be controlled and manipulated coherently.

**Online content**

Any methods, additional references, Nature Portfolio reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41567-023-02052-0.
53. Chauhan, K., Philip, J., De Silva, C. M., Hutchins, N. & Marusic, I. The turbulent/non-turbulent interface and entrainment in a boundary layer. *J. Fluid Mech.* **742**, 119–151 (2014).

54. da Silva, C. B., Dos Reis, R. J. & Pereira, J. C. The intense vorticity structures near the turbulent/non-turbulent interface in a jet. *J. Fluid Mech.* **685**, 165–190 (2011).

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Methods
Additional information on the methods can be found in Supplementary Section II.

Experimental chamber and actuation
The experimental chamber was fabricated by using a commercial 3D printer with ultraviolet-cured polymers (Objet VeroWhite and VeroBlack, Objet Connex 350, Stratasys), and was primarily used throughout the experiments. A windowed chamber made of acrylic with a similar geometry was also used to measure properties of vortex rings. See Supplementary Information for the design and the exact dimensions. An electric linear actuator (Copley Controls) controls the motion of the acrylic piston through signals output from a data acquisition board (PCI-6251, National Instruments). As the piston attached to the top surface lifts up, fluid gets pulled into the chamber through the orifices, creating eight vortex rings travelling towards the centre. A rubber flap attached to the top surface around the piston’s entry point prevents unwanted flow in or out of the chamber near the piston. We use a transmissive optical encoder (EM2, US Digital) to track the motion of the piston with sub-millimetre precision. With the tracking data, we extract two important parameters regarding the properties of the vortex rings: the formation number $L/D$ (ref. 33) (that is, the stroke ratio normalized by the orifice diameter) and the effective velocity of the piston $v_{\text{eff}}$ (Supplementary Section II). The former governs the radius and the stability of the generated vortex ring, and is a function of the diameter of the orifices $D_o$ and that of the piston $D_p$. The latter controls the speed of the vortex ring. To generate two sizes of vortex rings ($R_{\text{ring}} = 15$ mm, 23 mm), we used two settings: $(D_o, D_p) = (160.0 \text{ mm}, 23.6 \text{ mm})$ and $(56.7 \text{ mm}, 12.8 \text{ mm})$. The first setting offers a large blob of turbulence, suited for turbulent analysis through 2D particle image velocimetry. The second setting offers a blob of turbulence small enough with respect to the illuminated volume for 3D PTV to conduct the 3D flux measurements for Fig. 4 without clipping the blob. We tested effects of the different thickness of the orifices on the generated rings but found that it did not qualitatively affect the dynamics.

Velocity field extraction
To characterize the flow, we illuminated fluorescent polyethylene microspheres (diameter $d = 100 \mu m$, density $\rho = 1.090 \text{ g cc}^{-1}$; Cospheric) with a Nd:YLF single-cavity diode-pumped solid-state laser ($<40 \text{ mJ}$ per pulse, 527 nm). A high-speed camera captured the beads’ motion (Phantom v2515 or Phantom VEO4k, Vision Research) on a thin laser sheet (thickness 1 mm) for 2D PIV. We varied the frame rate of the cameras, depending on the speed of the vortex ring, ranging from 250 to 3,000 fps, while a ‘quarter rule’ 56 was always satisfied for the largest displacement observed. We extracted the velocity fields by using DaVis software (LaVision, Inc.), applying the pyramid algorithm 57 to generate a velocity field for turbulent analysis (energy spectrum, structure function, dissipation rate and turbulence length scales) as it was shown to extract the small-scale motion more accurately than the standard cross-correlational algorithm (Window Distortion Iterative Multigrid method 58).

For 4D measurements, we set up an array of three to four cameras to capture the motion of the same beads illuminated in a volume of $120 \text{ mm} \times 100 \text{ mm} \times 80 \text{ mm}$, created by two cylindrical lenses. The 3D particle tracking algorithm called ‘shake the box’ 59 detected $O(10^5)$ particles from the images of the different perspectives, and reconstructed their trajectories. Binning the Lagrangian velocities gave the structure function, dissipation rate and turbulence length scales) as it was shown to extract the small-scale motion more accurately than the standard cross-correlational algorithm (Window Distortion Iterative Multigrid method 58).

3D visualization
The Lagrangian trajectories obtained by 3D PTV were first characterized by their lifespan, travelled distance, average speed and position when first detected. We used this information to identify the particles transported by the vortex rings. The selected particles were then visualized as pathlines using Houdini rendering software (SideFX). The Supplementary Videos show the pathlines combined of the four recordings for each experiment (coherent reconnections and a turbulent state).

For the visualization of the mean flow energy, the mean turbulent energy and the Q-criterion, we used Dragonfly software (Object Research Systems).

Data availability
The data contained in the plots within this paper and other findings of this study are available from the corresponding author on reasonable request.

Code availability
The codes to handle 2D PIV and 3D PTV data, to compute energy spectra, structure functions and dissipation from velocity fields, and to visualize flows are available from the corresponding author upon reasonable request.

References
55. Gharib, M., Rambod, E. & Shariff, K. A universal time scale for vortex ring formation. J. Fluid Mech. 360, 121–140 (1998).
56. Raffel, M. et al. Particle Image Velocimetry: A Practical Guide (Springer, 2018).
57. Sciacchitano, A., Scarano, F. & Wieneke, B. Multi-frame pyramid correlation for time-resolved PIV. Exp. Fluids 53, 1087–1105 (2012).
58. Scarano, F. Iterative image deformation methods in piv. Meas. Sci. Technol. 13, R1 (2001).
59. Scharn, D., Gesemann, S. & Schröder, A. Shake-the-box: Lagrangian particle tracking at high particle image densities. Exp. Fluids 57, 70 (2016).

Acknowledgements
We thank N. Goldenfeld, G. Voth, F. Coletti and P. A. Davidson for insightful discussions and feedback and F. Coletti and L. Baker for discussion on the performance of PIV. We thank L. Biferale and F. Bonaccurso for sharing the simulation data of helical turbulence with us via the Smart-TURB database, as well as the Turbulence Research Group at Johns Hopkins University for access to the Johns Hopkins Turbulence Database. We also acknowledge Y. Ganan and R. Morton for help in performing the Gross-Pitavskii equation simulations. This work was supported by the Army Research Office through grant nos. W911NF-17-S-0002, W911NF-18-1-0046 and W911NF-20-1-0117, and by the Brown Science Foundation. We also acknowledge LaVision Inc. for support with PIV and PTV, and SideFX and Object Research Systems for granting software licences (for Houdini and Dragonfly, respectively) to visualize flows. The Chicago MRSEC is gratefully acknowledged for access to its shared experimental facilities (U.S. NSF grant DMR2011854). For access to computational resources, we thank the University of Chicago’s Research Computing Center and the University of Chicago’s GPU-based high-performance computing system (NSF DMR-1828629).

Author contributions
WT.M.I. initiated and supervised research. S.P. designed chamber actuation and performed proof of concept experiments. N.P.M. contributed to chamber design and contributed analytical tools. T.M. constructed the apparatus and the imaging system, performed all experiments reported in this paper and wrote the code to handle, process and visualize flow data. T.M. and WT.M.I. designed experiments, analysed data, performed modelling and wrote the paper.

Competing interests
The authors declare no competing interests.
Additional information

Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s41567-023-02052-0.

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Peer review information Nature Physics thanks Van Luc Nguyen and the other, anonymous, reviewer(s) for their contribution to the peer review of this work.

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