Observation of many-body Fock space dynamics in two dimensions

Yunyan Yao1,4, Liang Xiang1,4, Zexian Guo1, Zehang Bao1, Yong-Feng Yang2, Zixuan Song1, Haohai Shi1, Xuhao Zhu1, Feitong Jin1, Jiachen Chen1, Shibo Xu1, Zitian Zhu1, Fanhao Shen1, Ning Wang1, Chuanyu Zhang1, Yaozu Wu1, Yiren Zou1, Pengfei Zhang1, Hekang Li1, Zhen Wang1, Chao Song1, Chen Cheng2, Rubem Mondaini1,3, H. Wang1, J. Q. You1, Shi-Yao Zhu1, Lei Ying1,2 & Qiujiang Guo1

Quantum simulation provides platforms to study fundamental aspects of many-body physics in a controlled way, and to explore their implications for quantum technology. However, the dimension of the Hilbert space grows exponentially with the number of interacting particles, which means that investigations of strongly correlated problems such as quantum criticality and many-body localization in terms of few-body probes in real space are often insufficient. Here we demonstrate how to tackle such questions on a superconducting quantum processor from a Fock-space perspective. We map a many-body system onto an unconventional Anderson model on a network of many-body states, which allows the direct observation of wave-packet propagation in Fock space. We find a quantum-critical regime of anomalously enhanced wave-packet width and deduce a critical point from the maximum wave-packet fluctuations, which lends support to the two-dimensional many-body localization transition in finite-sized systems. Our results introduce an alternative picture for characterizing many-body dynamics and for exploring the controversial problems such as criticality and dimensionality. Moreover, the protocol is universal and scalable, and is therefore a promising strategy to solve a broader range of many-body problems on future quantum devices.

Strongly correlated particles in an isolated quantum system with appropriate perturbations trigger abundant physical phenomena, typified by the many-body version of quantum thermalization1–4, localization5–9, scarring10–13 and so on. There is great interest in their experimental realizations in various platforms14–17, ranging from fundamental physics to applications in quantum information, in particular as examples of potential quantum advantages in many-body quantum simulations18. Although tremendous experimental efforts have been devoted to understanding quantum thermalization19,20 and its breakdown21–23, there is still no strong consensus on further open problems such as the stability of the many-body localization (MBL) phase in higher dimensions22–24 and critical properties of the MBL transition25–27. So far, existing experimental explorations on these topics have been largely confined to the conventional framework in real space, focusing on
Fig. 1 | Quantum processor and schematic of many-body dynamics in Fock space. a, Bottom: optical micrograph of a 36-qubit superconducting quantum processor. Top: using 24 of these qubits, we emulate a hard-core Bose–Hubbard model on a 4 × 6 2D lattice. Each red (blue) sphere indicates a real-space qubit at the excited (ground) state, and lines represent the photon hopping strength connecting two sites (the intra-tetramer couplings J₁, the inter-tetramer couplings J₂, and the cross hoppings g₁), with their thicknesses indicating the programmable coupling strength. b, Fock-space representation of the real-space lattice in a, where each site s (denoted by a dot) represents a specific photon excitation configuration in the real-space lattice. The extensive local connectivity (grey lines) signifies all possible one-photon hoppings in Hamiltonian (1). The initial configuration s₀ is an apex of the network, marked by an orange star. All sites are arranged according to the Hamming distance D(s, s₀) away from it. The yellow circle (s₁) and the blue square (s₂) are two representative configurations corresponding to D(s, s₀) = 2 and L, respectively.

c, Fock-space visualization of the typical dynamics. A far-from-equilibrium initial state |s₀⟩ is prepared as a Fock state, whose wave packet is a unit impulse function located at D(s, s₀) = 0. The unitary dynamics result in its propagation and diffusion in the Fock-space network over time, where the long-time behaviour describes the equilibration properties. At the weak disorder regime, the system shows a thermalizing behaviour, and the wave packet quickly reaches the ergodic distribution (shaded grey region) with a maximum occurring at L/2 for the majority of states. A few scarred states, however, exhibit pendulum-like dynamics with slow thermalization, as visualized by the dashed curves and arrows. At strong disorders, the propagation of the wave packet is suppressed at D(s, s₀) < L/2, and its width is narrower than the ergodic case. Around the critical point (black triangle), the wave packet exhibits a broader width, implying stronger fluctuation.

The characterization of the dynamics of few-body observables such as imbalance and correlations, rather than the bipartite entanglement entropy (EE), is a hallmark of Fock-space localization. Moreover, the anomalous non-ergodic behaviour is represented by the localization in Fock space under strongly correlated disorders. This new approach has led to a series of novel insights, such as multi-fractal scaling of MBL eigenstates, emergent Hilbert-space fragmentation and nonergodic extended phase. Nevertheless, the Fock-space perspective is still relatively less popular than the real-space framework. An important reason for this is that experimental investigations along this line remain scarce, because conventional analysis in Fock space largely relies on quantification of the experimentally prohibitive inverse participation ratios (IPRs).

To shed light on these long-standing challenges, in this Article we experimentally demonstrate a new paradigm for probing many-body dynamics in Fock space, describing a universal and scalable protocol capable of exploring such controversial problems as MBL in higher dimensions and the associated quantum criticality. The underlying idea is illustrated in Fig. 1. An isolated many-body system in real space (Fig. 1a, upper panel) can be represented equivalently in Fock space (Fig. 1b), where each Fock-space site corresponds to a photon excitation configuration in real space, and their connectivities denote all allowed hoppings. Thus, the many-body dynamics of a far-from-equilibrium initial Fock (product) state |s₀⟩ can be regarded as a wave packet moving along the radial direction of the Fock-space network labelled by the Hamming distance D(s, s₀) = \sum_{m,n} |s_{mn} - s_{0m}| (Fig. 1c, left panel), where s_{mn} = 0 or 1 denotes the real-space site (m, n) being either in the ground or excited state.

Within this Fock-space approach, we employ a two-dimensional (2D) superconducting qubit array to experimentally characterize typical many-body dynamics, further exploring contentious areas of the MBL transition. We track how the wave packet propagates on the Fock-space network, providing an intuitive physical picture of thermalization and its breakdown (localization and scarring) from the Fock-space view (Fig. 1c, right panel). Quantum ergodicity is further qualified by the Bhattacharyya metric, and we find that only a finite fraction of the Fock-space is actively involved at large disorder strengths, a hallmark of Fock-space localization. Moreover, the anomalous non-monotonic behaviour of wave-packet width with growing disorder allows us to quantitatively identify a three-regime phase diagram for the finite-size 2D nonergodic transition, which is hard to capture for conventional real-space experimental observations. The critical disorder V_c is extracted by the maximum of wave-packet fluctuations in the disorder dependence. Remarkably, it agrees well with the numerical value by means of the experimentally inaccessible probe, the bipartite EE, further confirming the effectiveness of our protocol.
Experimental platform and protocol

To reveal the many-body dynamics in Fock space with the aforementioned approach, we utilize a 2D flip-chip superconducting quantum processor (Fig. 1a, lower panel). This provides a 6 × 6 transmon qubit lattice with long qubit energy relaxation times ($T_1$ of ~120 μs), high-fidelity site-resolved controllability (single-qubit fidelity of ~0.997) and tunable interactions (Supplementary Sections 1 and 2). Using a subset of 12 qubits, we effectively emulate a 4 × 6 hard-core Bose–Hubbard lattice in real space (Fig. 1a, upper panel) and its Hamiltonian (Supplementary Section 4) is given by

$$\frac{\hbar}{\hbar} = \sum_{m,n} (\mathcal{J}_m \mathcal{J}_n \mathcal{J}_{m+1,n} + \mathcal{J}_n \mathcal{J}_{m,n+1} + \text{h.c.}) + \sum_{m,n} \mathcal{V}_{m,n} \mathcal{J}_m \mathcal{J}_n + H_k$$

where $\mathcal{J}_{m,n}$ is the two-level raising (lowering) operator of qubit $(m,n)$ and $\hbar$ is the reduced Planck constant. The first term in equation (1) describes the kinetic motion of bosons, where $\mathcal{J}_m$ and $\mathcal{J}_n$ denote the strength of tunable nearest-neighbour hoppings along the $x$ and $y$ axes, respectively. The second term represents the local bosonic occupation energy, which can be adjusted individually for each site $(m,n)$ by tuning the qubit frequency. To mimic a 2D disordered system, $\mathcal{V}_{m,n}$ is chosen from the uniform random distribution $[-V, V]$. A perturbation term, $H_k = \mathcal{H}_k \sum_{m,n} (\mathcal{J}_{m,n} \mathcal{J}_{m+1,n} + \mathcal{J}_{m,n+1} \mathcal{J}_{m,n} + \text{h.c.})$, is associated to parasitic cross hoppings that naturally occur in the device. As shown in Fig. 1b, with the initial configuration $\mathcal{s}_0$, the apex, $N$ Fock-space sites $|\mathcal{s}\rangle$ can be sorted out as a 13-layer structure by the Hamming distance $d = 0, 2, \ldots, 24 \ (L)$, wherein each layer includes $C(L/2, d/2)$ sites. Together with the connectivity provided by the hoppings $|\mathcal{J}_{s}\rangle$, the Fock-space Hamiltonian (2) forms a quantum network with a double-cone structure.

The experimental observation starts with a Fock state $|\mathcal{s}_0\rangle$ by exciting half of the qubits via π-pulses, which enables the probe of the largest photon-number-conserved sector with a Hilbert space dimension of $N = 2, 704, 156$. After suddenly opening interactions by tuning qubits and couplers, the system undergoes the out-of-equilibrium evolution governed by the engineered many-body Hamiltonian above (see Supplementary Section 3 for the experimental sequences and calibrations). Finally, we extract the system dynamics with subsequent site-resolved simultaneous qubit readout after time $t$. To suppress readout errors and the decoherence effects of energy relaxation, we perform readout correction and a subsequent post-selection for the measured multi-qubit probabilities before further calculating observables (Supplementary Section 12). The maximum evolution time $t_{max} = 1,000 \text{ ns}$ is much longer than the typical tunnelling time $t_{tunn} = 32 \text{ ns}$, enabling observation close to equilibration, but sufficiently short compared with qubit relaxation and dephasing times. For detailed information about the decoherence effect and the finite-time effect see Supplementary Sections 13 and 14.

Wave-packet dynamics in Fock space

To describe the quantum dynamics within the Fock-space network, a dynamical radial probability distribution $\Pi(d, t)$ is introduced as

$$\Pi(d, t) = \sum_{|\mathcal{s}\rangle \in \{D(\mathcal{s}, \mathcal{s}_0) = d\}} |\langle \mathcal{s}\rangle e^{-\frac{\mathcal{H}_k}{\hbar}t} |\mathcal{s}_0\rangle|^2$$

which behaves as a wave packet and is interpreted as the probability that the many-body wavefunction appears at a Hamming distance $d$ away from the initial state $|\mathcal{s}_0\rangle$ at time $t$. In contrast with the experimentally inaccessible and static definition in terms of eigenstates $\Pi(d, t)$ quantitatively characterizes how an initial localized many-body wavefunction propagates in Fock space (Fig. 1c), being experimentally feasible with growing system sizes.

Examples of the dynamics of $\Pi(d, t)$ for thermalization, localization and scattering are shown in Fig. 2a–c, respectively. At $t = 0$, the initial state is a localized wave packet, so $\Pi(0, 0) = 1$. For thermalizing dynamics in the absence of disorder (Fig. 2a), a typical Fock state in the central part of the Hamiltonian spectrum $|\mathcal{s}\rangle$ (see Supplementary Section 9 for details) quickly and homogeneously spreads over the whole Fock space, equilibrating near $L/2$ (Supplementary Section 10), where the density of states is maximum. In contrast, under nonergodic dynamics ($V = 16J_0$), the wave packet does not propagate to the
large-Hamming-distance regime, staying around \((d < L/2)\) its initial state, ultimately suggesting localization in Fock space (Fig. 2b). Interestingly, however, the special state \(s^0_S\) (see Supplementary Section 5) shows a coherent periodic motion (Fig. 2c) in Fock space. Such weak ergodicity-breaking behaviour arises due to \(s^0_S\) having a large overlap with the rare non-thermal eigenstates, whose wavefunctions exhibit anomalously concentrated patterns in a small subspace of the Fock space. Because this special subspace is not decoupled but is weakly linked to the rest of the huge thermal Fock space by the inter-tetramer coupling, the system exhibits slow thermalization\(^{14}\) (Supplementary Section 5). It represents a many-body version of scarring analogous to scars of the periodic motions in the single-particle quantum stadium\(^{47}\). Section 5). It represents a many-body version of scarring analogous to

\[
\rho(t) = \sum_d \sqrt{\rho(d,t) I^{F_k}(d)}
\]

which quantifies the similarity between the dynamical wave packet \(\rho(d,t)\) and the ergodic one \(I^{F_k}(d)\).

Figure 3 shows the results for \(\mathcal{B}(t)\). The prepared initial states are far from equilibrium and thus \(\mathcal{B}(t = 0) \approx 1\). For \(V = 0\), the initial wave packet spreads over the entire space, indistinguishable from the ergodic ensemble \(I^{F_k}(d)\), so \(\mathcal{B}(t \to \infty) \approx 1\) for both thermal and scarred states. Despite the final thermal fate, the weak ergodicity-breaking mechanism leaves a slow-thermalization imprint on the scarred dynamics with periodic coherent oscillations (Fig. 3b). In the deep localized phase \((V \approx 16g_0)\), \(\mathcal{B}(t)\) approaches a value far less than 1, indicating that the wave packet is restricted to a finite fraction of the Fock space, signifying the strong violation of ergodicity. A small \(\mathcal{B}(t)\) means that only part of the Fock space actively contributes to the system dynamics, which is instructive for developing a decimation scheme of the Hilbert space to efficiently simulate MBL systems with numerics\(^{45,59}\).

**Signature of the 2D nonergodic transition**

In addition to characterizing many-body dynamics over different quantum phases, more importantly, our Fock-space approach provides a scalable way of exploring critical phenomena. Quantum-critical behaviour near the MBL transition currently lacks consensus\(^{56,57}\), and its locating method typically relies on global diagnostics (for example, bipartite EE and IPR)\(^{26,54–58}\), which are experimentally and numerically challenging for large systems (Supplementary Sections 8 and 11). By analysing the properties of the wave packet in detail, we find three regimes for the MBL crossover in our finite-sized 2D system.

We utilize \(\mathcal{B}(d)\) in the long-time limit \((t = 1,000\ ns, J = 31)\) to characterize the transition from the thermal to the MBL-like phase (whose approach to the thermodynamic limit in the latter requires confirmation). We introduce the normalized displacement \(x_i = \frac{1}{\sqrt{N}} \sum_k \sqrt{d_\Pi(d)}\) and the normalized width \(\Delta x = \frac{\sqrt{c_1}}{c_2} \sum_k d_\Pi(d) - L^2\) for a single wave packet \(\Pi(d)\) to quantify the properties of the wave packet, where \(c_2\) denotes the index of disorder realizations. For an ergodic wave packet, \(x_{\text{Erg.}} = 0.5\) and \(\Delta x_{\text{Erg.}} = 0.5\) (Supplementary Section 10).

Figure 4a displays the disorder-averaged displacement \(\langle x \rangle = \frac{1}{k} \sum_i x_i\) as a function of disorder strength \(V\), which is averaged over an ensemble of wave packets \(\langle \Pi(d) \rangle\) with \(k = 400\) combinations of random disorder realizations (Supplementary Section 9). Notably, \(\langle x \rangle\) is closely related to the local real-space autocorrelation function, indicating a preservation of local information for \(x_i < 0.5\) (refs. 15,59,60). Deep in the thermal phase with \(V = 0\), \(\langle x \rangle \approx 0\), in quantitative agreement with \(x_{\text{Erg.}}\). As disorder strength grows, \(\langle x \rangle\) decreases monotonically, meaning that the propagation of the wave packet in Fock space is hindered by disorder, and the initial local information is preserved, suggesting strong evidence of nonergodicity. Its behaviours are compatible with the numerical results of bipartite EE (S/\(S_p\) (Fig. 4a, inset). Here, \(S_p = 0.5[\ln(2L - 1)]\) is the Page value for random states in Fock space\(^{41}\).

As shown in Fig. 4b, the second-order quantity \(\langle \Delta x \rangle = \frac{1}{k} \sum_i (\Delta x_i)^2\) without real-space correspondence, exhibits much richer features and allows the identification of three typical regimes for the disorder-induced transition from the thermal phase to the MBL-like phase. In the weak disorder regime \(V < 2J_0\), we find a plateau of \(\langle \Delta x \rangle = \Delta x_{\text{Erg.}}\), indicating a thermal phase, where wave packets almost coincide perfectly with the ideal thermal one, \(I^{F_k}(d)\) (Fig. 4d). A critical regime of \(2J_0 < V \lesssim 10J_0\) is identified by an anomalous increase of wave-packet width with \(\Delta x \approx \Delta x_{\text{Erg.}}\), which shows a good agreement with the anomalous slow-relaxation regime reported in ref. 29. If we take \(V = 8J_0\) as an example (Fig. 4e), the wave packet in this regime exhibits a broader distribution with an enhanced sample-to-sample fluctuation for displacement \(x_i\). In the strong disorder regime, \(V \approx 10J_0\), the width plummets below \(\Delta x_{\text{Erg.}}\), implying localization in Fock space.
Fig. 4 | Signature of nonergodic transition in 2D system. a–c, Disorder-averaged normalized displacement $\langle x \rangle$ (a), normalized width $\langle \Delta x \rangle$ (b) and system fluctuation $\langle \sigma \rangle$ (c) of wave packets at $t = 1,000$ ns ($Jt = 31$) as a function of disorder strength $V$, where the experimental data (green squares) obtained by averaging over 400 random disorder realizations are compared with numerics (shaded areas with boundary lines). Insets in a and c: simulation results for the disorder-averaged bipartite EE $\langle S \rangle$ and its standard deviation $\Delta S$, exhibiting qualitatively similar behaviour to $\langle x \rangle$ and $\langle \sigma \rangle$, respectively. Error bars are the standard error of the statistical mean. d–f, Disorder-averaged wave packets $\langle \Pi(d) \rangle$ (the shaded regions) for $V = J_0$ (d, red), $8J_0$ (e, orange) and $16J_0$ (f, blue) over 400 disorder realizations. Squares connected with lines in each panel are two representative realizations of $\langle \Pi(d) \rangle$ at the corresponding disorder strength.

To locate the critical disorder, we use the system fluctuation $\langle \sigma \rangle = \sqrt{\frac{2}{N} \sum_i d^2 \langle \Pi(d) \rangle - L^2 (\langle x \rangle)^2}$, the width of disorder-averaged wave packet $\langle \Pi(d) \rangle$ (Fig. 4e) as the diagnostic, where $\langle \Pi(d) \rangle = \frac{1}{L} \sum_i \Pi_i(d)$ (Supplementary Section 10 provides a detailed discussion). It comes from sample-to-sample randomness, including both displacement fluctuations and width variations. Enhanced fluctuations are observed, as shown in Fig. 4c. A putative critical disorder $V_c'$ is estimated by the peak position of $\langle \sigma \rangle$. Remarkably, the numerics for $\Delta S$ (the standard deviation of bipartite EE) predicts the same value (Fig. 4c, inset), validating the $V_c'$ estimated within our approach.

The observed physical picture above can be explained by a dilute thermal bubbles model, which establishes the connection between thermal avalanche theory and the renormalization group approach for understanding the MBL transition. Currently, the existence of MBL in a 2D system remains widely debated. Despite numerical evidence, thermal avalanche theory argues on the instability of a 2D MBL phase due to thermal bubbles occurring in rare regions of locally weak disorders. A final conclusion requires proper scaling and the verification of the delocalization mechanism in the presence of such bubbles, which is beyond the scope of this work.

**Conclusion and outlook**

We have experimentally demonstrated a novel protocol for exploring many-body physics from a fresh perspective—Fock space. By mapping the out-of-equilibrium many-body dynamics onto a wave packet propagating on a Fock-space network, we provide a clear characterization of the thermalization and its breakdown in Fock space, described by the dynamical trajectory of the wave packet and the statistical emergence of an ergodic ensemble. In Fock space, key features of MBL, inhibition of wave-packet propagation, are observed dynamically, and many-body scarring is identified by local oscillations. Besides that, our protocol also allows us to experimentally capture the elusive quantum-critical behaviours across the finite-size MBL transition in 2D systems. A three-regime picture of such a transition and a critical disorder $V_c'$ are quantitatively identified experimentally, which is typically challenging for traditional real-space observations.

Methodologically, our protocol provides a simple yet effective way to quantitatively reveal the nature of the MBL transition, even for critical behaviours of higher-dimensional systems. It is worth stressing that, unlike the experimentally and numerically prohibitive bipartite EE and IPR in large systems, our protocol is scalable, platform-independent and robust to readout errors (Supplementary Section 12), making it a universal experimental playground to solve contentious questions in future larger devices.

Although our experiments have already provided important insights and implications for understanding MBL in Fock space, conclusive arguments on open questions involved in this work, such as the stability of MBL in higher dimensions and the role of rare regions near the critical point, need further investigation. It will be fascinating to develop a finite-size scaling method based on our protocol, the application of which to larger quantum devices, surpassing sizes amenable to classical computations, has a larger chance to settle the ongoing conundrum.

**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/s41567-023-02133-0.
6. Basko, D., Aleiner, I. & Altshuler, B. Metal-insulator transition in a weakly interacting many-electron system with localized single-particle states. Ann. Phys. 321, 1126–1205 (2006).
7. Nandkishore, R. & Huse, D. A. Many-body localization and thermalization in quantum statistical mechanics. Annu. Rev. Condens. Matter Phys. 6, 15–38 (2015).
8. Abanin, D. A., Altman, E., Bloch, I. & Serbyn, M. Colloquium: many-body localization, thermalization and entanglement. Rev. Mod. Phys. 91, 021001 (2019).
9. Alet, F. & Laflorencie, N. Many-body localization: an introduction and selected topics. Comptes Rendus Phys. 19, 498–525 (2018).
10. Turner, C. J. et al. Weak ergodicity breaking from quantum many-body scars. Nat. Phys. 14, 745–749 (2018).
11. Serbyn, M., Abanin, D. A. & Papić, Z. Quantum many-body scars and weak breaking of ergodicity. Nat. Phys. 17, 675–685 (2021).
12. Bernien, H. et al. Probing many-body dynamics on a 51-atom quantum simulator. Nature 551, 579–584 (2017).
13. Scherg, S. et al. Observing non-ergodicity due to kinetic constraints in tilted Fermi–Hubbard chains. Nat. Commun. 12, 4490 (2021).
14. Schreiber, M. et al. Observation of many-body localization of interacting fermions in a quasirandom optical lattice. Science 349, 842–845 (2015).
15. Smith, J. et al. Many-body localization in a quantum simulator with programmable random disorder. Nat. Phys. 12, 907–911 (2016).
16. Xu, K. et al. Emulating many-body localization with a superconducting quantum processor. Phys. Rev. Lett. 120, 050507 (2018).
17. Roushan, P. et al. Spectroscopic signatures of localization with interacting photons in superconducting qubits. Science 358, 1175–1179 (2017).
18. Mi, X. et al. Information scrambling in computationally complex quantum circuits. Science 374, 1479–1483 (2021).
19. Neill, C. et al. Ergodic dynamics and thermalization in an isolated quantum system. Nat. Phys. 12, 1037–1041 (2016).
20. Kaufman, A. M. et al. Quantum thermalization through entanglement in an isolated many-body system. Science 353, 794–800 (2016).
21. Lukin, A. et al. Probing entanglement in a many-body localized system. Science 364, 256–260 (2019).
22. de Roeck, W. & Huveneers, F. Stability and instability towards delocalization in many-body localization systems. Phys. Rev. B 95, 155129 (2017).
23. Potirniche, I.-D., Banerjee, S. & Altman, E. Exploration of the stability of many-body localization in d > 1. Phys. Rev. B 99, 205149 (2019).
24. Doggen, E. V. H., Gornyi, I. V., Mirlin, A. D. & Polyakov, D. G. Slow many-body delocalization beyond one dimension. Phys. Rev. Lett. 125, 155701 (2020).
25. Potter, A. C., Vasseur, R. & Parameswaran, S. A. Universal properties of many-body delocalization transitions. Phys. Rev. X 5, 031033 (2015).
26. Khemani, V., Lim, S. P., Sheng, D. N. & Huse, D. A. Critical properties of the many-body localization transition. Phys. Rev. X 7, 021013 (2017).
27. Dumitrescu, P. T., Goremnykina, A., Parameswaran, S. A., Serbyn, M. & Vasseur, R. Kosterlitz-Thouless scaling at many-body localization phase transitions. Phys. Rev. B 99, 094205 (2019).
28. Choi, J. et al. Exploring the many-body localization transition in two dimensions. Science 352, 1547–1552 (2016).
29. Bordia, P. et al. Probing slow relaxation and many-body localization in two-dimensional quasiperiodic systems. Phys. Rev. X 7, 041047 (2017).
30. Rispoli, M. et al. Quantum critical behaviour at the many-body localization transition. Nature 573, 385–389 (2019).
31. Landig, R. et al. Quantum phases from competing short- and long-range interactions in an optical lattice. Nature 532, 476–479 (2016).
32. Görg, F. et al. Enhancement and sign change of magnetic correlations in a driven quantum many-body system. Nature 553, 481–485 (2018).
33. Welsh, S. & Logan, D. E. Simple probability distributions on a Fock-space lattice. J. Phys. Condens. Matter 30, 405601 (2018).
34. Altshuler, B. L., Gefen, Y., Kamenev, A. & Levitov, L. S. Quasiparticle lifetime in a finite system: a nonperturbative approach. Phys. Rev. Lett. 78, 2803–2806 (1997).
35. Macê, N., Alet, F. & Laflorencie, N. Multifractal scalings across the many-body localization transition. Phys. Rev. Lett. 123, 180601 (2019).
36. Logan, D. E. & Welsh, S. Many-body localization in Fock space: a local perspective. Phys. Rev. B 99, 045131 (2019).
37. De Tomasi, G., Hetterich, D., Sala, P. & Pollmann, F. Dynamics of strongly interacting systems: from Fock-space fragmentation to many-body localization. Phys. Rev. B 100, 214313 (2019).
38. Roy, S. & Logan, D. E. Fock-space correlations and the origins of many-body localization. Phys. Rev. B 101, 134202 (2020).
39. Roy, S. & Logan, D. E. Fock-space anatomy of eigenstates across the many-body localization transition. Phys. Rev. B 104, 174201 (2021).
40. De Luca, A., Altshuler, B. L., Kравtsov, V. E. & Scardicchio, A. Anderson localization on the Bethe lattice: nonergodicity of extended states. Phys. Rev. Lett. 113, 046806 (2014).
41. De Tomasi, G., Amini, M., Bera, S., Khaymovich, I. M. & Kравtsov, V. E. Survival probability in generalized Rosenzweig-Porter random matrix ensemble. SciPost Phys. 6, 014 (2019).
42. Wang, Y., Cheng, C., Liu, X.-J. & Yu, D. Many-body critical phase: extended and nonthermal. Phys. Rev. Lett. 126, 080602 (2020).
43. Benalcazar, W. A., Bernevig, B. A. & Hughes, T. L. Quantized electric multipole insulators. Science 357, 61–66 (2017).
44. Karamlou, A. H. et al. Quantum transport and localization in 1D and 2D tight-binding lattices. npj Quantum Inf. 8, 35 (2022).
45. De Tomasi, G., Khaymovich, I. M., Pollmann, F. & Warzel, S. Rare thermal bubbles at the many-body localization transition from the Fock space point of view. Phys. Rev. B 104, 024202 (2021).
46. Zhang, P. et al. Many-body Hilbert space scarring on a superconducting processor. Nat. Phys. 19, 120–125 (2022).
47. Keller, E. J. Bound-state eigenfunctions of classically chaotic Hamiltonian systems: scars of periodic orbits. Phys. Rev. Lett. 53, 1515–1518 (1984).
48. Yan, Z. et al. Strongly correlated quantum walks with a 12-qubit superconducting processor. Science 364, 753–756 (2019).
49. Braumüller, J. et al. Probing quantum information propagation with out-of-time-ordered correlators. Nat. Phys. 18, 172–178 (2021).
50. Aherne, F. J., Thacker, N. A. & Rockett, P. I. The Bhattacharyya metric as an absolute similarity measure for frequency coded data. Kybernetika 34, 363–368 (1998).
51. Aoki, H. Real-space renormalisation-group theory for Anderson localisation: decimation method for electron systems. J. Phys. C Solid State Phys. 13, 3369–3386 (1980).
52. Pietracaprina, F. & Laflorencie, N. Hilbert-space fragmentation, multifractality and many-body localization. Ann. Phys. 435, 168502 (2021).
53. Šuntajs, J., Bonča, J., Prosen, T. & Vidmar, L. Quantum chaos challenges many-body localization. Phys. Rev. E 102, 062144 (2020).
54. Kjäll, J. A., Bardarson, J. H. & Pollmann, F. Many-body localization in a disordered quantum Ising chain. Phys. Rev. Lett. 113, 107204 (2014).
55. Luitz, D. J., Latflorencie, N. & Alet, F. Many-body localization edge in the random-field Heisenberg chain. Phys. Rev. B 91, 081103 (2015).
56. Evers, F. & Mirlin, A. D. Anderson transitions. *Rev. Mod. Phys.* **80**, 1355–1417 (2008).
57. Luitz, D. J., Alet, F. & Laflorencie, N. Universal behavior beyond multifractality in quantum many-body systems. *Phys. Rev. Lett.* **112**, 057203 (2014).
58. Šuntajs, J., Bonča, J., Prosen, T. & Vidmar, L. Ergodicity breaking transition in finite disordered spin chains. *Phys. Rev. B* **102**, 064207 (2020).
59. Hauke, P. & Heyl, M. Many-body localization and quantum ergodicity in disordered long-range Ising models. *Phys. Rev. B* **92**, 134204 (2015).
60. Guo, Q. et al. Stark many-body localization on a superconducting quantum processor. *Phys. Rev. Lett.* **127**, 240502 (2021).
61. Page, D. N. Average entropy of a subsystem. *Phys. Rev. Lett.* **71**, 1291–1294 (1993).
62. Goremykina, A., Vasseur, R. & Serbyn, M. Analytically solvable renormalization group for the many-body localization transition. *Phys. Rev. Lett.* **122**, 040601 (2019).
63. Foo, D. C. W., Swain, N., Sengupta, P., Lemarié, G. & Adam, S. A stabilization mechanism for many-body localization in two dimensions. Preprint at https://arxiv.org/pdf/2202.09072.pdf (2022).
64. Wahl, T. B., Pal, A. & Simon, S. H. Signatures of the many-body localized regime in two dimensions. *Nat. Phys.* **15**, 164–169 (2018).
65. Kshetrimayum, A., Gohil, M. & Eisert, J. Time evolution of many-body localized systems in two spatial dimensions. *Phys. Rev. B* **102**, 235132 (2020).
66. Théveniaut, H., Lan, Z., Meyer, G. & Alet, F. Transition to a many-body localized regime in a two-dimensional disordered quantum dimer model. *Phys. Rev. Res.* **2**, 033154 (2020).
67. Chertkov, E., Villalonga, B. & Clark, B. K. Numerical evidence for many-body localization in two and three dimensions. *Phys. Rev. Lett.* **126**, 180602 (2021).
68. Luitz, D. J., Laflorencie, N. & Alet, F. Extended slow dynamical regime close to the many-body localization transition. *Phys. Rev. B* **93**, 060201 (2016).

**Publisher's note** Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Springer Nature or its licensor (e.g. a society or other partner) holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.

© The Author(s), under exclusive licence to Springer Nature Limited 2023
Data availability
The data presented in the figures and that support the other findings of this study are available at https://doi.org/10.5281/zenodo.7733236.

Code availability
All the relevant source codes are available from the corresponding authors upon reasonable request.

Acknowledgements
The device was fabricated at the Micro-Nano Fabrication Center of Zhejiang University. We acknowledge support from Zhejiang Province Key Research and Development Program (grant no. 2020C01019) and the National Natural Science Foundation of China (grants nos. 92065204, U20A2076, 12274368, U2230402, 12111530010, 12222401, 11974039, 12174167, 12047501 and 11934010). Q.G. is also supported by the Zhejiang Provincial Natural Science Foundation of China under grant no. LQ23A040006. L.Y. is also supported by the National Key R&D Program of China (grant no. 2022YFA1404203).

Author contributions
Q.G. and L.Y. proposed the idea; Y.Y., L.X. and Z.B. conducted the experiment and analysed the data under the supervision of Q.G. and H.W.; Z.B., Z.G. and Y.-F.Y. performed the numerical simulation under the supervision of Q.G., C.C. and L.Y.; H.L. and J.C. fabricated the device under the supervision of H.W.; Q.G., L.Y., R.M. and H.W. co-wrote the manuscript; S.-Y.Z. supervised the whole project. All authors contributed to the experimental set-up, discussions of the results and development of the manuscript.

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/s41567-023-02133-0.

Correspondence and requests for materials should be addressed to Lei Ying or Qiujiang Guo.

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

Reprints and permissions information is available at www.nature.com/reprints.