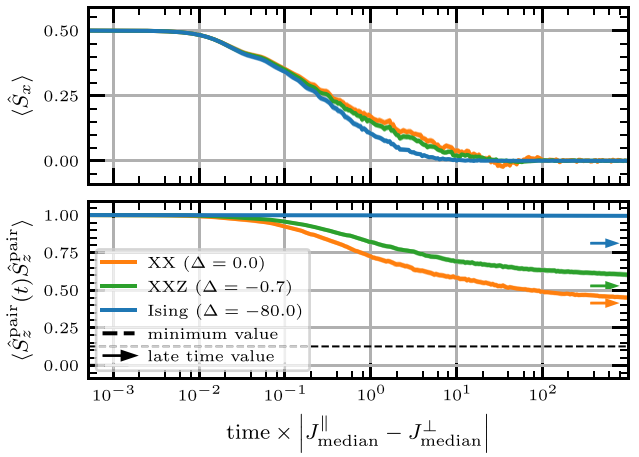

FIG. 4. Dynamics of the pair magnetization autocorrelator. Numerical simulation of $N = 16$ spins in $d = 1$ with interaction exponent $a = 2$ and a mean interspin distance $a_0 = 20r_b$. Line width shows statistical uncertainty from disorder averaging.

directly study and compare the relaxation dynamics of three different quantum spin systems far from equilibrium.

The central finding of this study is the robustness of the functional form of the relaxation curves with respect to parameter changes in the microscopic spin model, even across models featuring different symmetries, and the choice of initial state (cf. Appendix E). This discovery raises a fundamental question about the universality of relaxation dynamics in spatially disordered spin systems. To address this question comprehensively, we presented an approximate description of the system based on pairs of spins, exhibiting excellent agreement with both numerical simulations and experimental data. Moreover, this effective model is integrable and thus features an extensive number of conserved quantities allowing for an exact solution.

To assess the quality of the effective model, we studied the decay of these effectively conserved quantities in small systems via exact methods. We found them to decay on a much slower timescale, which might indicate that the system behaves prethermaly: On the early timescale, the effective pair model to lowest order holds, and thus the relaxation appears universal.

The observed robustness hinges on a number of system properties: Firstly, universal relaxation is known to hold only in the strong disorder regime [21]. Secondly, we expect the dynamics to depend on global parameters of the system like the spatial dimension d and the range of interaction α, which both determine the distribution of couplings $J_{i,j}^{\perp,\parallel}$ (e.g., the stretch power has been analytically derived to be $\beta = d/\alpha$ in the case of the Ising model [27]). Therefore, it is crucial to compare experimental data only where the distributions of interaction strengths are comparable such that the underlying universal behavior becomes evident (see also Appendix C where the distribution of coupling for the experiments shown in this article are shown).

The accurate approximation of the relaxation dynamics by an integrable model of pairs indicates that the time evolution of disordered quantum spin systems cannot be viewed as direct thermalization. Instead, even at later times when the global magnetization has completely relaxed to zero, the system can still exhibit local characteristics originating from quasiconserved pairs of spins. In order to investigate the deviations from the pair model and, hence, from the prethermal state, future experiments will require single-site resolution [50]. Further investigations could also study the influence of the energy density of the initial state on the dynamics, indicative of a possible phase transition [51].

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APPENDIX A: ENGINEERING HEISENBERG XXZ HAMILTONIANS BY DIFFERENT COMBINATIONS OF RYDBERG STATES

In the following, we provide a comprehensive description of how to engineer this Hamiltonian with different combinations of Rydberg states [40,41]. Especially, this gives us the opportunity to explain how to engineer an Ising Hamiltonian in a spin system realized by two different Rydberg states.

For general spin systems with global $U(1)$ symmetry, the coupling terms can be obtained by calculating the matrix elements of the interaction Hamiltonian $\hat{H}$. The Ising term

$$J_{ij}^{\parallel} = (E_{\uparrow_i\uparrow_j} + E_{\downarrow_i\downarrow_j}) - (E_{\downarrow_i\uparrow_j} + E_{\uparrow_i\downarrow_j}) \tag{A1}$$

is defined as the energy difference between spins being aligned and being antialigned. Here, $E_{\alpha_i\beta_j} = \langle \alpha_i\beta_j|\hat{H}|\alpha_i\beta_j\rangle$ are the interaction energy of spin i and j with $\alpha, \beta \in [\uparrow, \downarrow]$. The exchange term is determined by

$$J_{ij}^{\perp} = \langle \downarrow_i\uparrow_j|\hat{H}|\uparrow_i\downarrow_j\rangle. \tag{A2}$$

For a system consisting of states with opposite parity, such as $|\downarrow\rangle = |nS\rangle$ and $|\uparrow\rangle = |nP\rangle$ [see Fig. 1(b)], where n is the principal quantum number, the dominant coupling is a direct dipolar interaction, which can be described by the Hamiltonian

$$\hat{H}_{\text{DDI}} = \frac{\hat{\mathbf{d}}_i \cdot \hat{\mathbf{d}}_j - 3(\hat{\mathbf{d}}_i \cdot \mathbf{e}_{r_{ij}})(\hat{\mathbf{d}}_j \cdot \mathbf{e}_{r_{ij}})}{r_{ij}^3}, \tag{A3}$$