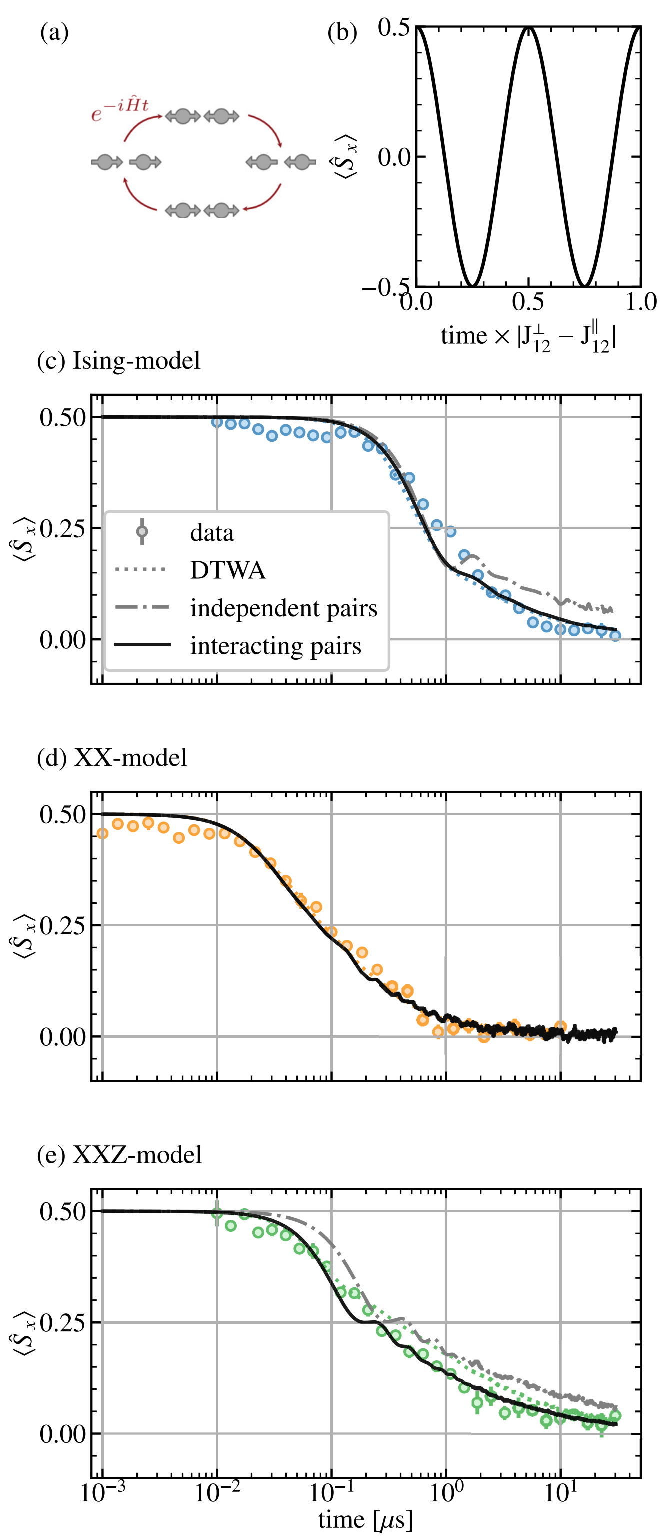

FIG. 3. Effective description by localized pairs. (a) Illustration of the oscillation of a single pair under an arbitrary XXZ Hamiltonian. A fully polarized state $|\rightarrow\rightarrow\rangle$ (left) evolves via the maximally entangled Bell state $1/\sqrt{2}(|\rightarrow\rightarrow\rangle + |\leftarrow\leftarrow\rangle)$ (top) to the state $|\leftarrow\leftarrow\rangle$ (right). Then, it returns to the origin via the other Bell state $1/\sqrt{2}(|\rightarrow\rightarrow\rangle - |\leftarrow\leftarrow\rangle)$ (bottom). (b) Oscillation of the magnetization for a single pair initialized in $|\rightarrow\rightarrow\rangle$. [(c)–(e)] Comparison of the relaxation dynamics obtained by the pair approximation with/without effective Ising terms (solid black line/grey dash-dotted line) and with DTWA (dotted line) and the experimental data of Fig. 2 for Ising (c), XX (d), and XXZ model (e).

This explains the rescaling found from the experimental data with $\text{median}_i \max_j |J^{\perp}_{ij} - J^{\parallel}_{ij}|$.

V. SEPARATION OF TIMESCALES IN SPIN DYNAMICS

In the previous section, we revealed that the relaxation dynamics of a single-body observable is well captured by an ensemble of pairs with Ising-like interactions. This simple description in terms of pairs provides an integrable effective Hamiltonian, which is valid not only at early times but agrees surprisingly well with the data over the entire relaxation process, which lasts for over three decades in time. In the following section, we will more quantitatively address the question of whether the magnetization of each pair is conserved by evaluating the pair autocorrelator given by $\langle \hat{S}^{\text{pair}}_z(t)\hat{S}^{\text{pair}}_z \rangle$, where $\hat{S}^{\text{pair}}_z = \hat{s}^i_z + \hat{s}^j_z$. If the pair picture is perfect or if the system is an Ising model, this quantity stays $\langle \hat{S}^{\text{pair}}_z(t)\hat{S}^{\text{pair}}_z \rangle = 1$. On the other hand, if the correlations in the system are fully decohered, the autocorrelator assumes its minimal value of $\langle \hat{S}^{\text{pair}}_z(t)\hat{S}^{\text{pair}}_z \rangle = \frac{2}{N}$ for a system of size N due to symmetry constraints.

Our numerics presented in Fig. 4 for $N = 16$ spins in $d = 1$ with interaction exponent $\alpha = 2$ reveals three important points. Firstly, at $t|J^{\parallel}_{\text{median}} - J^{\perp}_{\text{median}}| \approx 0.2$ the global magnetization $\langle \hat{S}_x \rangle$ has decayed almost by half, while the pairs' magnetization autocorrelators are still close to 1. This justifies our simplistic pair picture and highlights the regime of universal dynamics. Secondly, at intermediate times up to 10^2, the global magnetization relaxes fully to zero while the autocorrelator still features slow dynamics. This illustrates the existence of two timescales. Observing two distinct timescales shows that the system has not yet reached thermal equilibrium once the magnetization has relaxed to zero [17,22] but rather hints at prethermal behavior [12,14,16,49]. This generally means that a system does not directly relax to its "true" thermal state, but instead reaches a prethermal state. This is still a thermal state but with respect to a different, prethermal Hamiltonian, which in our case only contains mostly Ising-like interactions among pairs. At very late times, this prethermal description ceases to be a reliable description, but even in the infinite time limit (derived by the diagonal ensemble and indicated by arrows in Fig. 4), the pair autocorrelator remains at $\approx 1/2$, which is significantly above the lower limit of $\frac{2}{N} = 1/8$. This indicates that our integrable pair model is still a reasonable description of the system even at late times.

VI. CONCLUSION

Our paper demonstrates the ability of Rydberg atom quantum simulators to synthesize a variety of many-body Hamiltonians on a single experimental platform. By choosing the appropriate state combination, we realized XX, XXZ, and for the first time, a quantum Ising model within the Rydberg manifold. This versatility of the platform has enabled us to