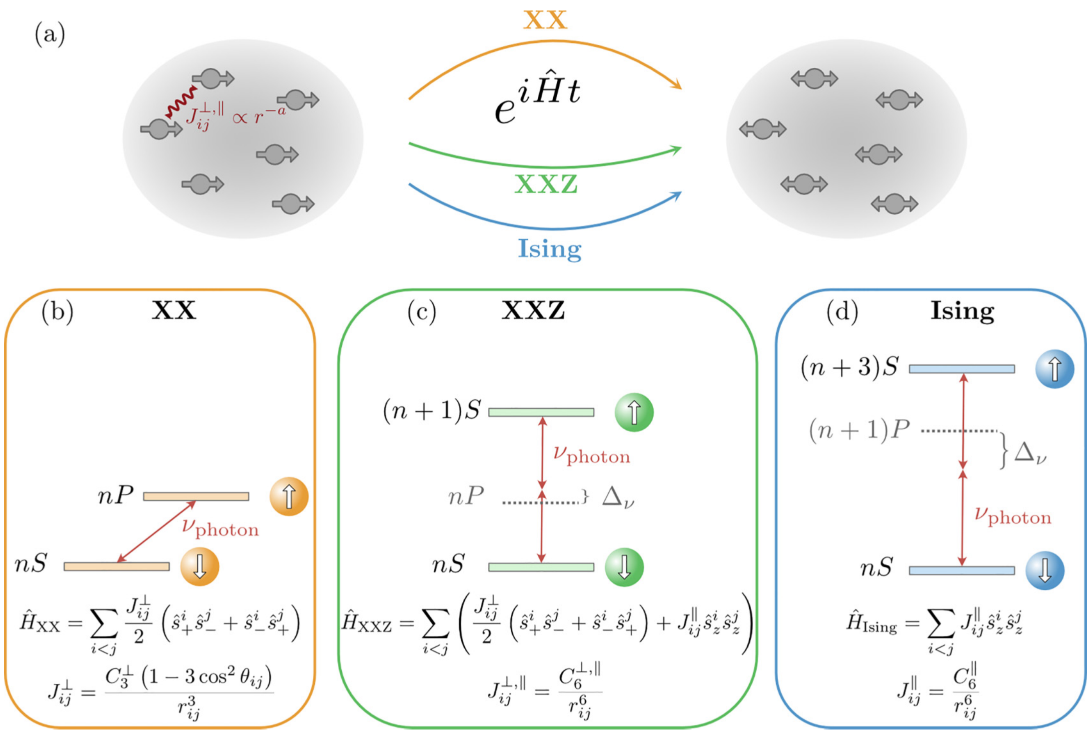


FIG. 1. Rydberg quantum simulator platform. (a) Illustration of out-of-equilibrium disordered spin systems relaxing with respect to different Hamiltonians. (b) Illustration of the experimental realization of a Heisenberg XX Hamiltonian by coupling a Rydberg $|nS\rangle$ state to a $|nP\rangle$ state, possessing opposite parity. The interaction is of dipolar nature and falls off as $r_{ij}^{-3}$. Coupling two Rydberg states with the same parity results in a Heisenberg XXZ Hamiltonian for state combinations $|nS\rangle$ and $|(n+1)S\rangle$ (c), while state combinations $|nS\rangle$ and $|(n+3)S\rangle$ results in a Ising Hamiltonian (d). In the two latter cases, the interactions are of van der Waals nature with a $r_{ij}^{-6}$ dependence.

features an extensive number of conserved quantities, i.e., it is integrable. For nonintegrable models, where no analytic solution exists, generic mechanisms for describing the relaxation dynamics after a quantum quench remain largely unknown. Investigating the exact time evolution numerically is challenging due to the exponential growth of the Hilbert space with system size in quantum many-body systems. Semiclassical simulations, neglecting quantum effects beyond initial quantum fluctuations, suggest that nonintegrable Heisenberg XYZ Hamiltonians present out-of-equilibrium dynamics that follows a stretched exponential law like the Ising model independent of their symmetry [28]. An alternative route is implementing the desired unitary time evolution experimentally using quantum simulation experiments with tunable parameters, which is the approach we pursue here [29–32].

In this paper, we use different combinations of states of highly excited Rydberg atoms to realize different types of spin Hamiltonians thus making use of the full versatility of this platform [9,21,33–37]. Rydberg atoms are ideally suited to study unitary quantum dynamics because the timescales of the interacting dynamics vastly exceed those of the typical decoherence mechanisms. We observe the relaxation dynamics of three different Heisenberg Hamiltonians: the integrable Ising model and the nonintegrable XX and XXZ models with power-law interactions and positional disorder [see Fig. 1(a)]. For all models, we observe the same characteristic decay of magnetization, well described by a stretched exponential function, which causes the data to collapse onto a single curve after the appropriate rescaling of time. We show that this robust behavior is directly linked to the presence of strong disorder, which allows deriving an effective, integrable model consisting of pairs of spins.

## II. HEISENBERG SPIN SYSTEMS ON A RYDBERG-ATOM QUANTUM SIMULATOR

We consider an interacting spin-1/2 system described by the following Heisenberg Hamiltonian ($\hbar = 1$)

$$\hat{H} = \sum_{i<j}\left(J_{ij}^{\perp}/2(\hat{s}_+^i\hat{s}_-^j + \hat{s}_-^i\hat{s}_+^j) + J_{ij}^{\parallel}\hat{s}_z^i\hat{s}_z^j\right). \qquad (1)$$

Here, $\hat{s}_\pm^i = \hat{s}_x^i \pm i\hat{s}_y^i$, where $\hat{s}_\alpha^i(\alpha \in x, y, z)$ are the spin-1/2 operator of spin $i$ and $J_{ij}^{\perp,\parallel} = C_a^{\perp,\parallel}/r^a$. These types of Heisenberg XXZ Hamiltonians with disordered couplings feature a rich phenomenology of different phases and relaxation behaviors [38]. The Ising case, where $J_{ij}^{\perp} = 0$, features additional symmetries under local spin rotations $\hat{s}_z^i$ that commute with the Hamiltonian, which make the Ising model integrable. For $J_{ij}^{\perp} \neq 0$, $\hat{s}_z^i$ are no longer conserved and the Hamiltonian is nonintegrable. We provide a comprehensive description of how to engineer this Hamiltonian with different combinations of Rydberg states in the Appendix [39,40]. Figure 1 illustrates the state combinations that can be used to realize the Heisenberg XX, XXZ, and Ising models. For the rest of this paper, the three spin models are realized by state combinations $|61S\rangle - |61P\rangle$ (XX, $J^{\parallel}/J^{\perp} = 0$,