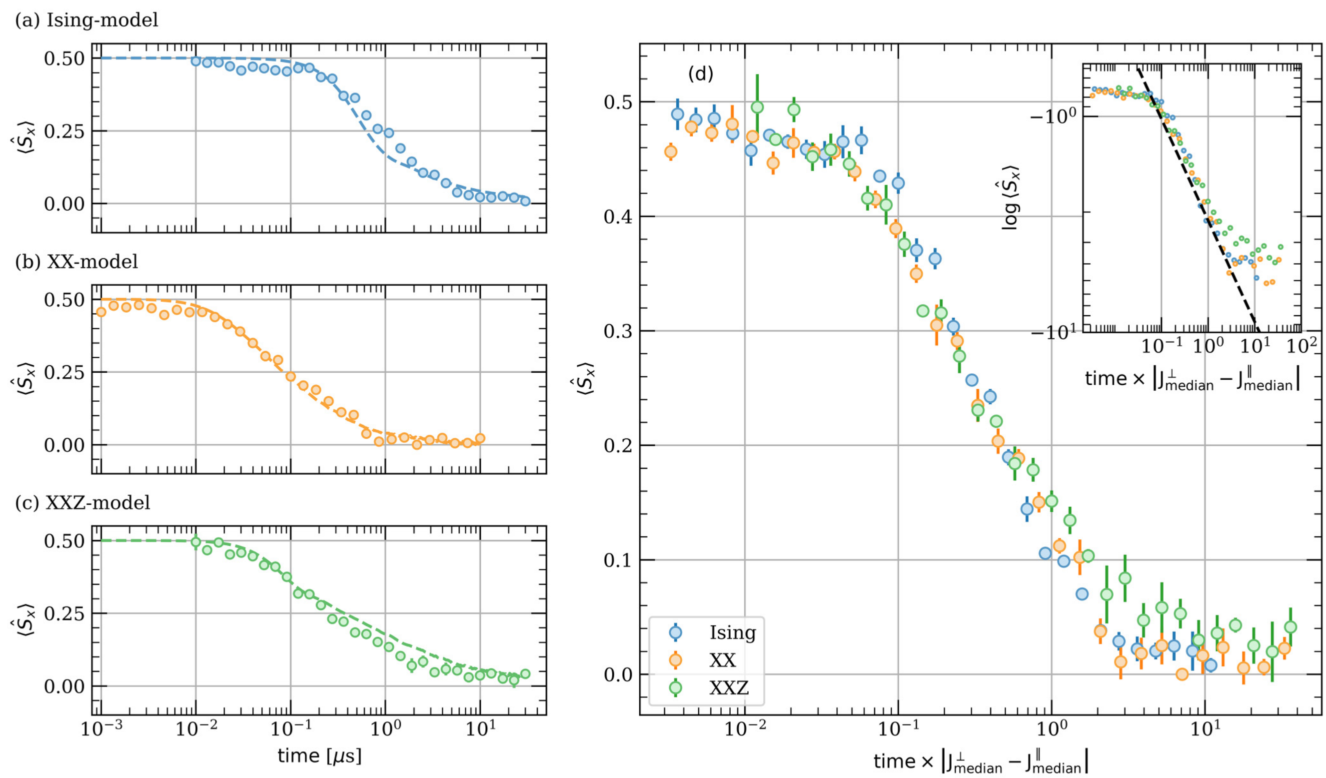

FIG. 2. Relaxation dynamics of disordered quantum spin systems. Magnetization dynamics as a function of time for the Ising model (a), the XX model (b), and the XXZ model (c). The dashed lines stem from DTWA simulations. (d) Magnetization dynamics of the three models as a function of the time rescaled by the typical interaction strength $2\pi\,|J^{\perp}_{\mathrm{median}} - J^{\parallel}_{\mathrm{median}}| = 2.3$ MHz (Ising model), 21 MHz (XX model), 7.6 MHz (XXZ model). (Inset) Data points of (c) plotted on as loglog vs log. The dashed line is a guide to the eye, indicating a stretched exponential relaxation with $\beta = 0.5$. The error bars denote the standard error of the mean.

$a = 3$), $|61S\rangle - |62S\rangle$ (XXZ, $J^{\parallel}/J^{\perp} = -0.7$, $a = 6$), and $|61S\rangle - |64S\rangle$ (Ising, $J^{\parallel}/J^{\perp} = -400$, $a = 6$).

III. EXPERIMENTAL OBSERVATION OF MODEL INDEPENDENT RELAXATION DYNAMICS

The experiment starts with trapping rubidium-87 atoms loaded in a crossed dipole trap at a temperature of 20 μK (see Appendix for experimental details). The atoms are excited from the ground $|g\rangle = |5S_{1/2}, F = 2, m_F = 2\rangle$ to the Rydberg state $|61S_{1/2}, m_j = 0.5\rangle$ by a two-photon transition with red (780 nm) and blue (480 nm) lasers that are detuned by $2\pi \times 98$ MHz from the intermediate state $|e\rangle = |5P_{3/2}, F = 3, m_F = 3\rangle$. For this state, the Rydberg lifetime of 100 μs exceeds the duration of the spin experiment of 30 μs. The excitation process leads to a three-dimensional cloud of $\mathrm{N} \approx 80 - 250$ Rydberg atoms that are distributed randomly. The van der Waals interaction during the excitation process imposes a minimal distance of $r_{\mathrm{bl}} \approx 10$ μm between the spins (Rydberg blockade effect). The state $|61S_{1/2}, m_j = 0.5\rangle$ is the $|\downarrow\rangle$ state of all three different spin systems, the main difference is the second Rydberg states that is addressed by choosing proper microwave coupling using an AWG setup (see Appendix for details).

After having excited the ground state atoms to the down spin state, we implement a Ramsey protocol in our Rydberg experiment. To initialize the dynamics a first $\pi/2$-microwave pulse is performed, which sets the whole system is the state $|\rightarrow\rangle^{\otimes \mathrm{N}} = 1/\sqrt{2}(|\uparrow\rangle + |\downarrow\rangle)^{\otimes \mathrm{N}}$ and we let the system evolve over 30 μs. A second $\pi/2$ pulse at a different readout phase followed by optical de-excitation and field ionization allows a tomographic measurement of the x magnetization $\langle \hat{S}_x\rangle = \sum_i \langle \hat{s}^i_x\rangle$ [21].

The resulting relaxation dynamics of the Ising, Heisenberg XX, and XXZ models are shown in Figs. 2(a)–2(c). At early times, the magnetization seems to be almost perfectly conserved at $\langle \hat{S}_x\rangle = 0.5$ before the relaxation begins. This effect is attributed to the Rydberg blockade that induces a maximal interaction strength that determines the system's fastest timescale. For each model, the system relaxes to zero magnetization, which can be understood by considering symmetry arguments: Indeed, the magnetization can be rewritten using the commutator relation for Pauli matrices $\langle \hat{S}_x\rangle = -i\langle[\hat{S}_y, \hat{S}_z]\rangle$. The latter term vanishes for each eigenstate $|\phi\rangle$ of the XXZ Hamiltonian because each eigenstate is also an eigenstate of $\hat{S}_z|\phi\rangle = \sum_i \hat{s}^{(i)}_z|\phi\rangle = S_z|\phi\rangle$ due to the global U(1) symmetry leading to $\langle[\hat{S}_y, \hat{S}_z]\rangle = S_z\langle[\hat{S}_y, 1]\rangle = 0$. The timescale of the dynamics occurring within less than 10 μs is comparable with the typical interaction strengths in the megahertz regime depending on the realized Heisenberg model (details on the distribution of interaction timescales can be found in the Appendix).

To compare the relaxation curves to numerical predictions, the spatial distribution of Rydberg spin positions needs to