Scalable spin squeezing in three dimensions

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Motivation for scalable spin squeezing

Spin-squeezed states: the paradigmatic example of *metrologically useful* entanglement

- Entanglement is a key for enabling quantum enhanced metrology, but not all entangled states are metrologically useful.
- In spin-squeezed states, entanglement leads to lower variance in a global spin operator than the standard quantum limit (SQL) (see evolution figure below).
- Squeezing has previously been realized with only long-range (all-to-all or dipolar $1/r^3$) interactions [2-4].
- For the first time we show spin squeezing in a 3D sample with only contact interactions.

Background: Heisenberg magnets

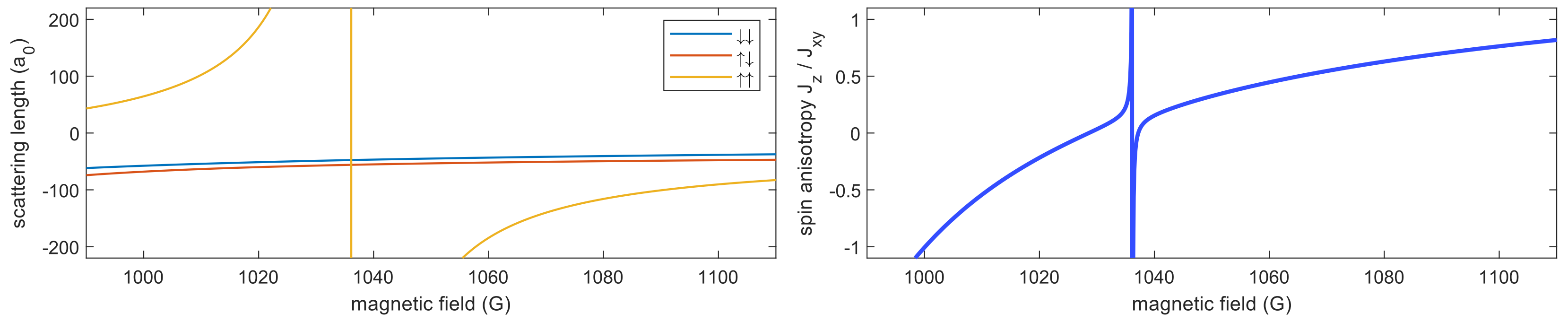
- Our quantum simulator can realize a Heisenberg Hamiltonian with tunable interactions J_{xy}, J_z:

$$H = \sum_{\langle ij \rangle} J_{xy}(S_i^x S_j^x + S_i^y S_j^y) + J_z S_i^z S_j^z$$

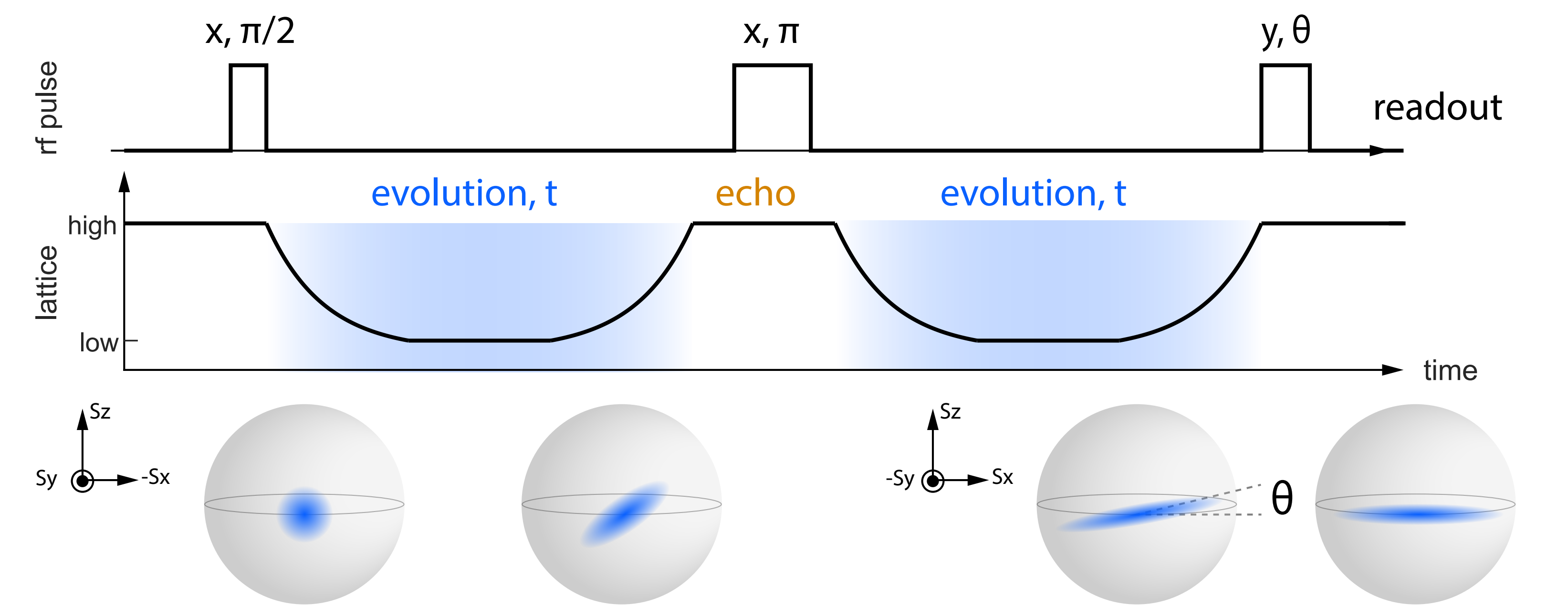
- It was recently shown theoretically [1] that for $-1 < J_z/J_{xy} < 1$ and a 3D lattice, an initial product state can be *scalably* squeezed, where the optimal achievable squeezing grows with system size.

Experimental setup

- Two hyperfine states of lithium-7 comprise an effective two-level system $|\uparrow\rangle$ and $|\downarrow\rangle$. While loaded in a $N = 1$ Mott insulator with no density fluctuations, the spin model above is effectively realized.
- The spin-spin anisotropy J_z/J_{xy} can be tuned by varying scattering length which varies as a function of magnetic field B around Feshbach resonances.
- We are limited to contact interactions, which means only nearest-neighbor spins can interact.



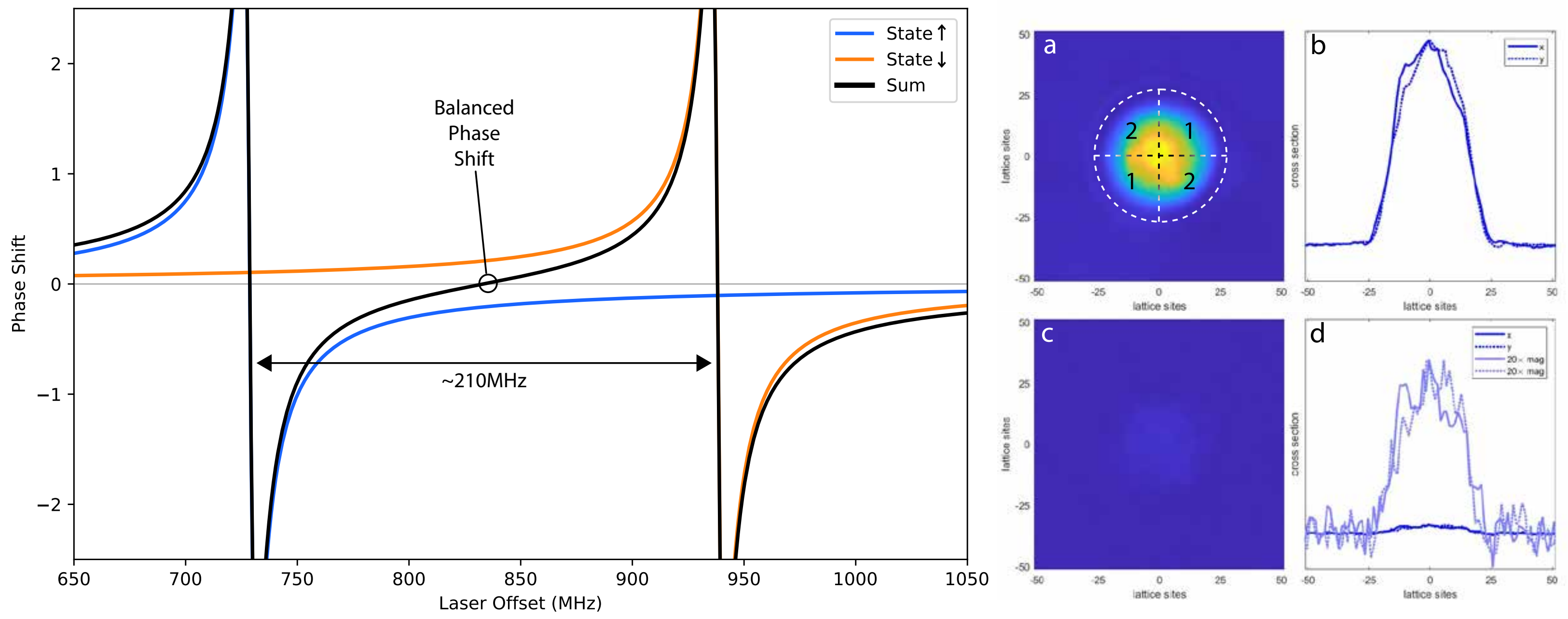
- We load $N = 30,000$ atoms into a 3D optical lattice, initialized in the $|Y+\rangle^{\otimes N}$ state with a RF pulse.
- We turn on interactions and let system evolve by reducing lattice depth. Then S_z is measured by rotating the sample by angle θ along the Y axis with a RF pulse.
- A spin echo was also used to mitigate decoherence due to magnetic field drifts and inhomogeneity.



Methods: Differential measurements

For a specific rotation angle θ, squeezing is measured as the decreased variance of the small population difference between the $|\uparrow\rangle$ and $|\downarrow\rangle$ states, or S_z. To overcome technical noise and exceed standard quantum limit, we employ several differential measurement techniques:

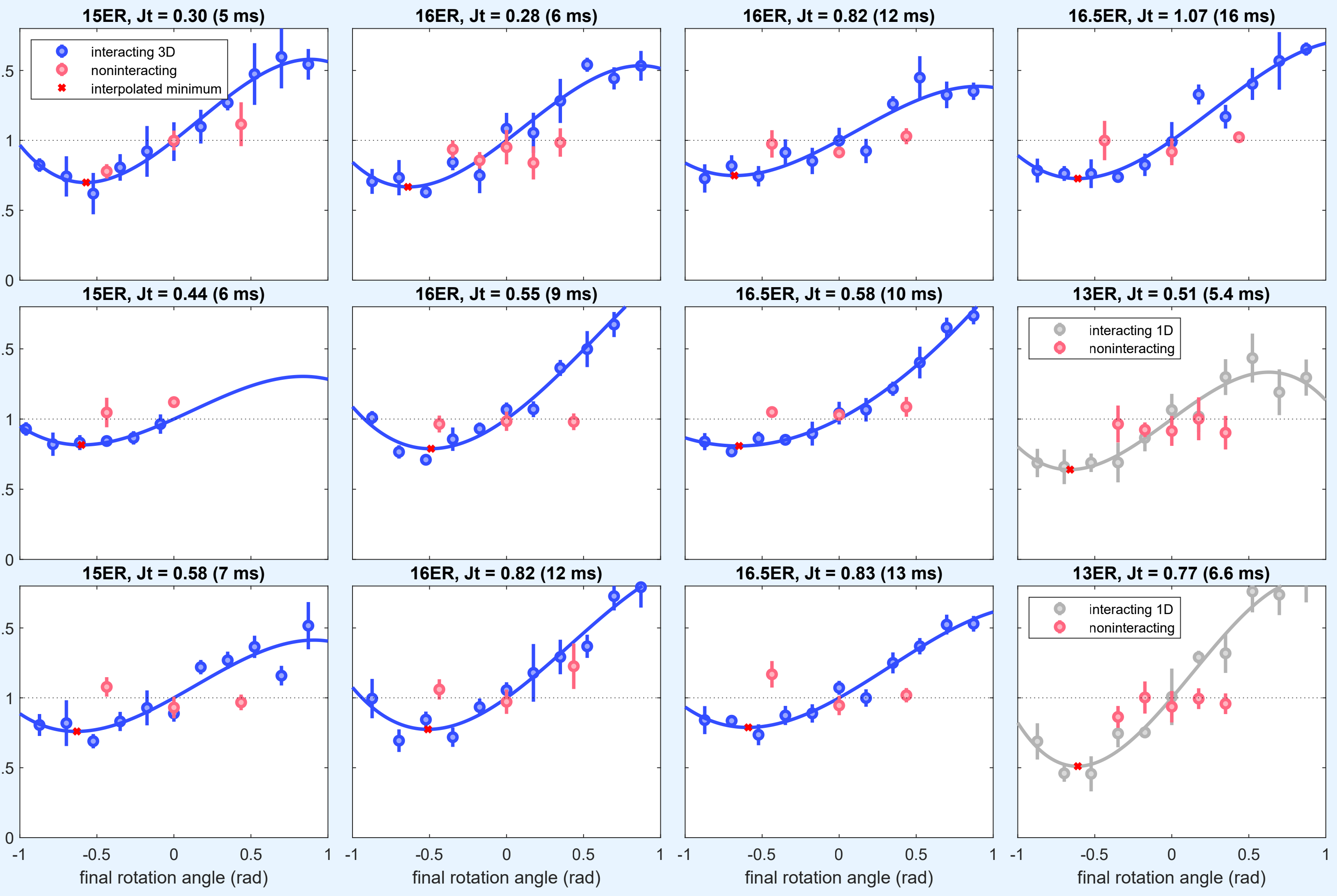
- **Polarization contrast imaging**. By detuning our imaging laser between two states, photons receive equal and opposite phase shifts. Combining this with a co-propagating reference in orthogonal polarization, we convert phase to intensity variation with a circular polarizer. This gives a background-free measurement of S_z.
- **Co-magnetometry**. Magnetic noise even at the 10^{-6} level (1 mG out of 1000 G) translates to phase noise during evolution. Despite the use of low noise electronics and spin echo, a random global phase is still present. To mitigate this effect, we perform a differential measurement where we subtract S_z of area 1 from that of area 2.



Results

We observe 1 - 2 dB of squeezing at the optimum rotation angle.

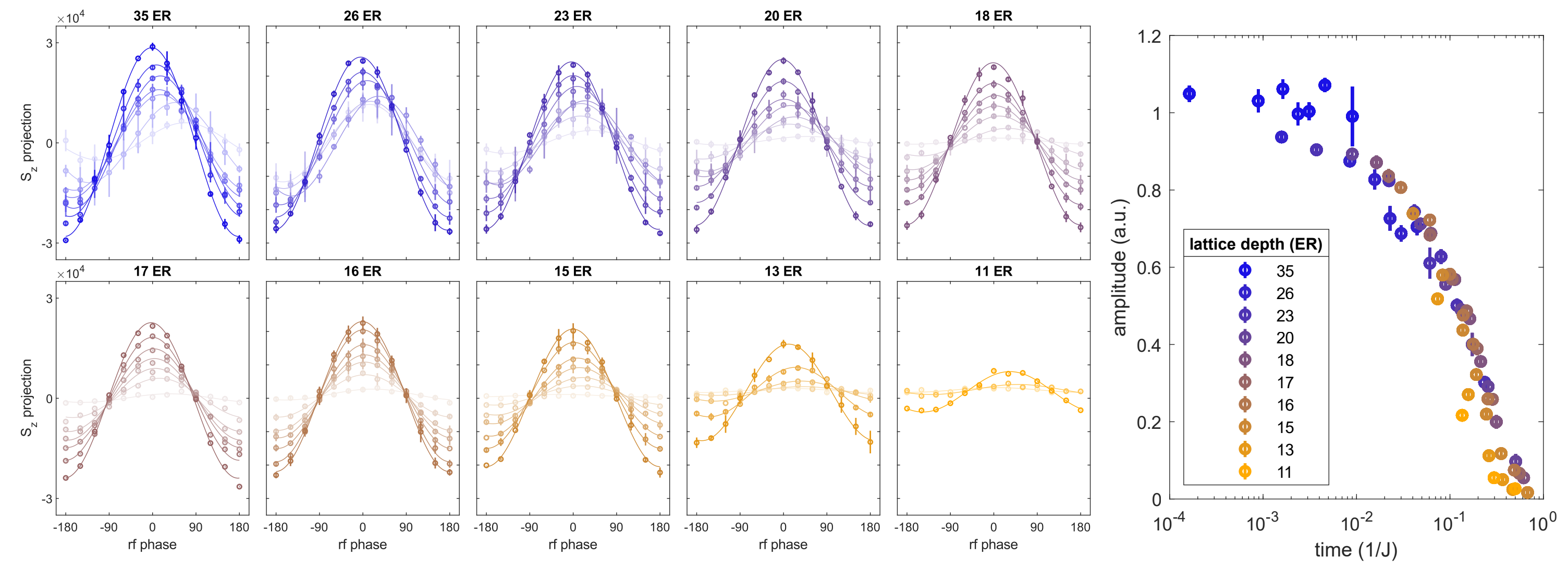
- Squeezing is observed for $J_z/J = 0$ and 0.5, as well as various lattice depths V_0 and evolution times Jt.
- Blue (red) circles are variances for interacting (non-interacting) systems.
- We also see (transient, non-scalable) squeezing in 1D (gray circles) as predicted by theory.
- Solid curves are polynomial fits to guide the eye and red crosses are minimum of that fit.



Discussion

We experience additional variance due to technical effects.

- Theory predicts 5 dB of squeezing within $t = 1/J_{xy}$, but only ≈2 dB was observed.
- Our system decoheres into a random mixture of $|\uparrow\rangle$ and $|\downarrow\rangle$ on a timescale of $\tau \approx 100$ ms.
- Moreover, there is an extra decay of the total spin length S that appears to scale with J_{xy}, which could arise due to mobile holes within the cloud.
- We observe up to 25% atom loss during imaging, which increases the measured variance of the system.



Future directions

To improve squeezing, we plan to:

- Use an optical gradient to fix mobile holes in the sample.
- Investigate the 1D Hamiltonian, where the interplay between transient squeezing and mobile holes may be easier to analyze.
- Explore trotterized evolution, where the time evolution of 3D Hamiltonian is broken down into 3 steps of 1D evolution.
- Improve imaging schemes with deeper lattices to prevent tunneling-induced losses or speckle imaging.

Conclusions

We achieve $\approx 2dB$ spin squeezing in a sample of $30,000$ atoms in a 3D lattice with only contact interactions.

- This protocol is scalable to larger system sizes. Scalability is currently only limited by our sources of technical noise and perhaps the presence of holes or double-occupancies in our Mott insulator.
- We also observe transient, non-scalable squeezing in 1D.

Acknowledgments

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