Demonstrating Quantum-Enhanced Sensing with Short-Ranged Interactions

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Introduction

Quantum sensors offer metrological performance beyond quantum standard limit using entanglement. Generating entanglement requires interactions.

Entanglement using a 1D chain of 51 ions with state-dependent interactions characterized by a distance power-law decay is demonstrated.

$$J_{i,j} = J_0|i-j|^{-\alpha}$$

Such a sensor can possibly behave as a one-axis-twisting (OAT) model.

Short-range Interactions:
- Particularly add undesirable complications
- Allow for single particle control within the quantum sensor

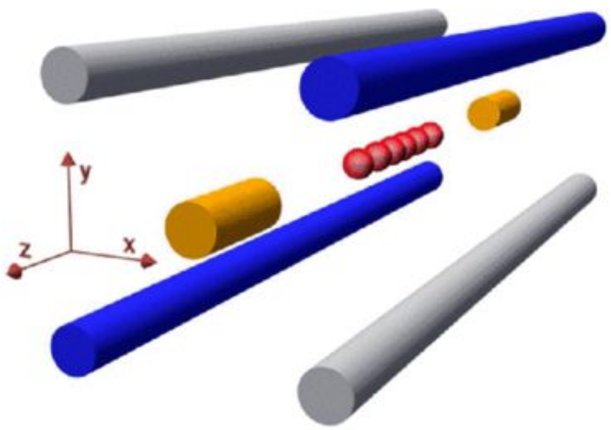
Long-range Interactions:
- Offer full connectivity, enhancing the rate of entanglement
- Lack the desired single-particle control

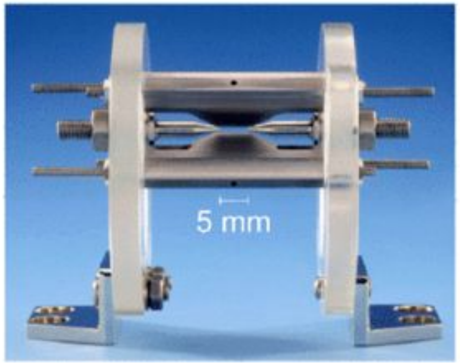
Trapped ions exhibit both single particle control and all-to-all interactions.

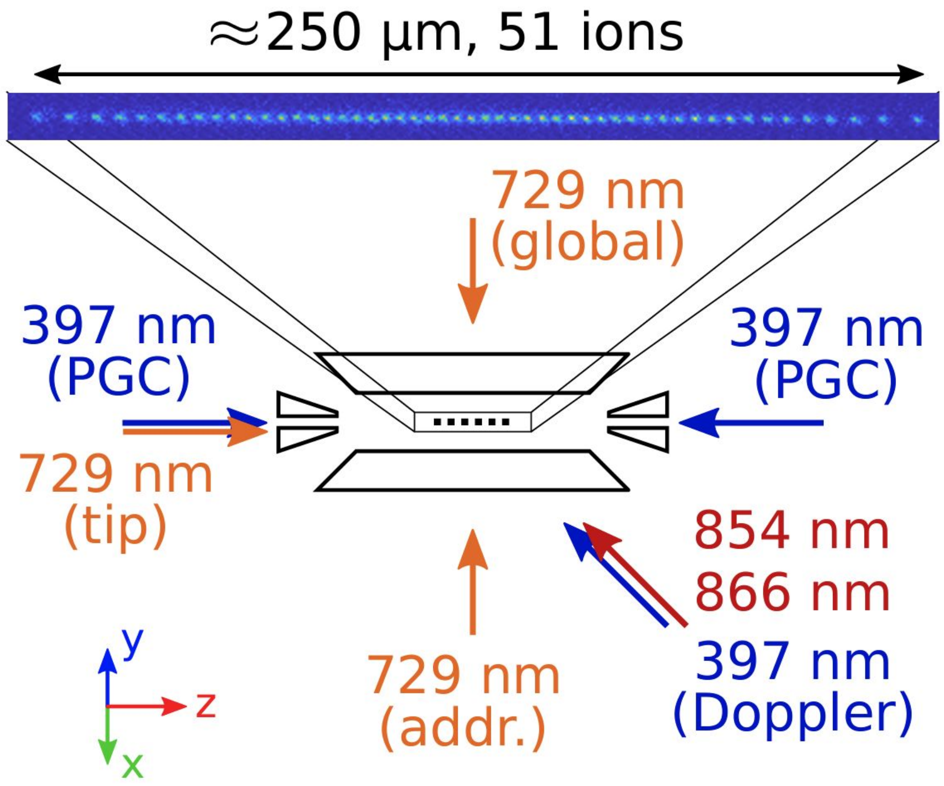
Systems exhibiting short-ranged interactions potentially generate entanglement for metrology at a level comparable to all-to-all interacting systems.

Can they match the same level of spin-squeezing?

Experimental Setup







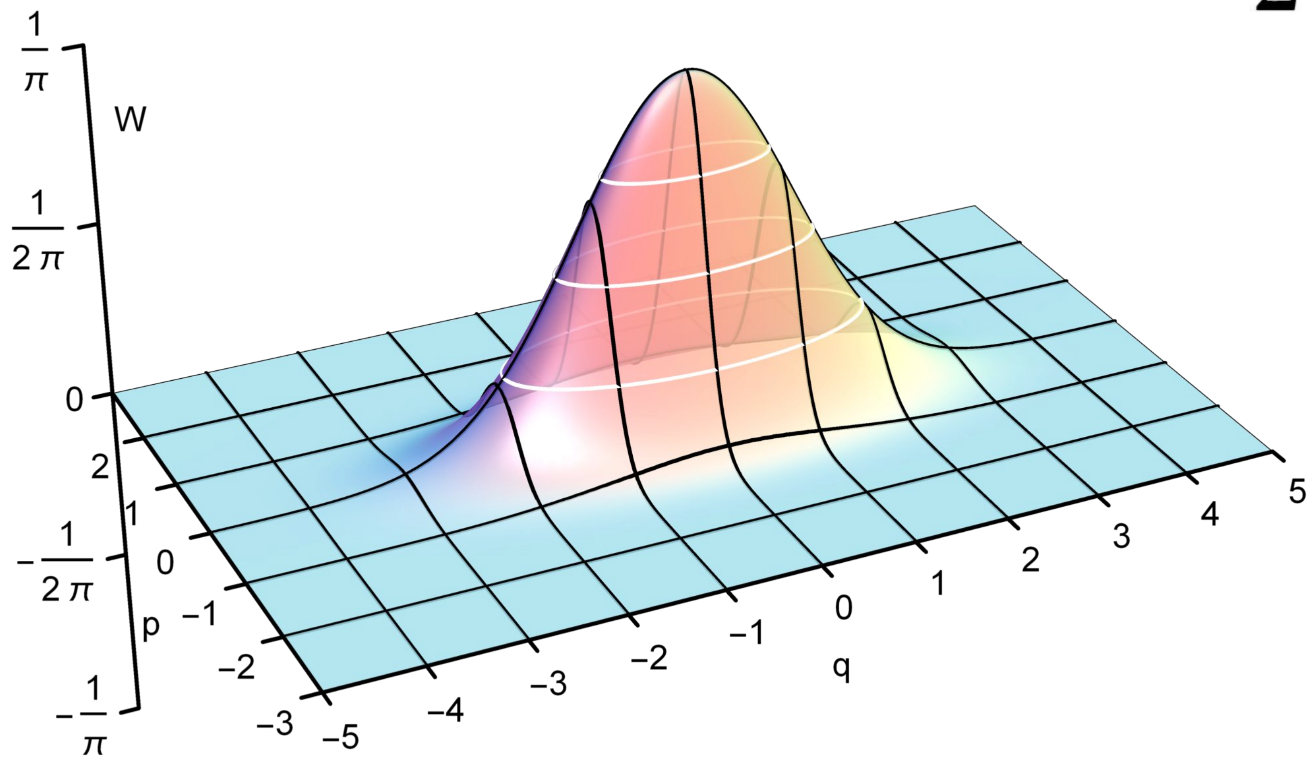
Linear Paul Trap. Elongated blades used for rf and two conical tips for the DC electrodes.

Counter-propagating beams creating a polarization gradient axially for cooling.

arXiv:1407.3493, Page 20 & arXiv:2112.10655, Page 2

Squeezed States

$$\Delta x \Delta p \geq \frac{\hbar}{2}$$



https://en.wikipedia.org/wiki/Squeezed_coherent_state

Theoretical Models

OAT Model

$$\hat{H}_{\mathrm{OAT}} = \frac{\chi}{2}\sum_{i<j}^{N} \hat{\sigma}_i^z \hat{\sigma}_j^z,$$

(all-to-all interaction)

Power-law Ising Model

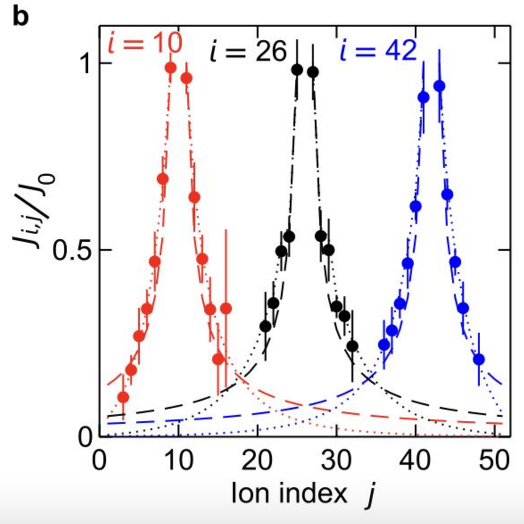
$$\hat{H}_{\mathrm{PL-Ising}} = \frac{1}{2}\sum_{i<j} J_{i,j} \hat{\sigma}_i^z \hat{\sigma}_j^z,$$

Power-law XX Model

$$\hat{H}_{\mathrm{PL-XX}} = \sum_{i<j} J_{i,j}\left(\hat{\sigma}_i^+ \hat{\sigma}_j^- + \hat{\sigma}_i^- \hat{\sigma}_j^+\right)$$

Power-law Transverse Field Ising Model

$$\hat{H}_{\mathrm{PL-TFI}} = \sum_{i<j} J_{ij} \hat{\sigma}_i^x \hat{\sigma}_j^x + B \sum_i \hat{\sigma}_i^z$$



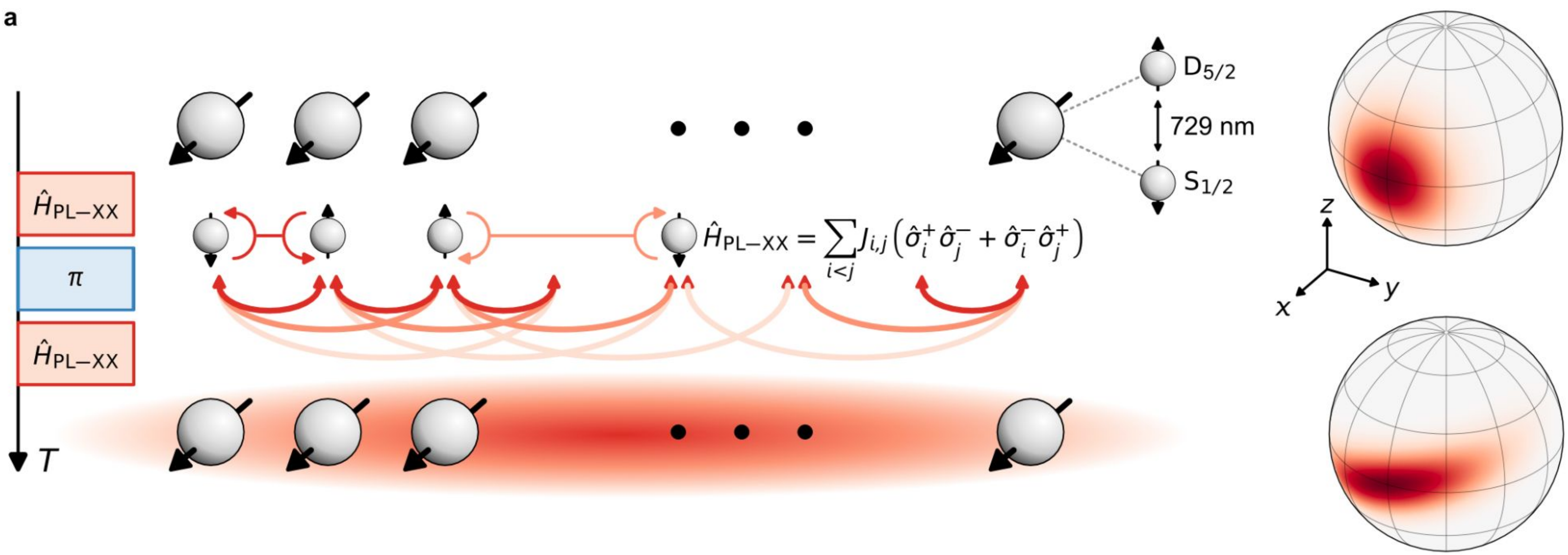
$$J_{i,j} = J_0 |i-j|^{-\alpha}$$

Experimental sequence

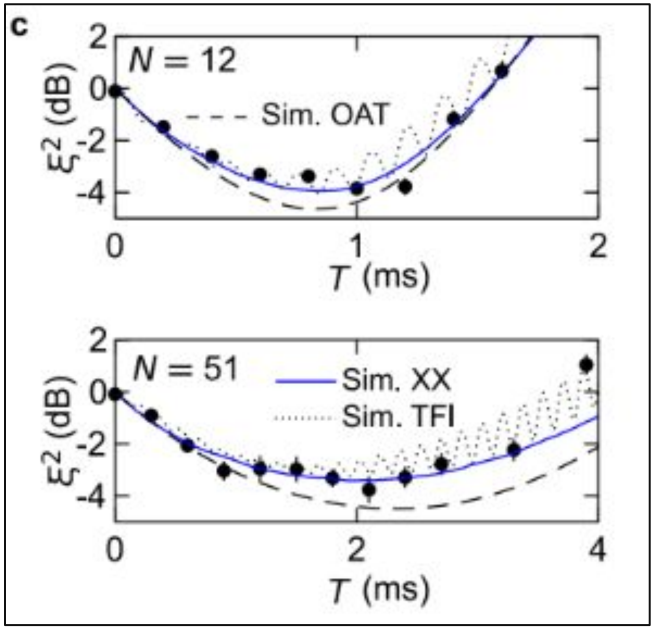
1. Prepare a CSS state polarized along +x.

2. Evolve this state under the XX interaction for a variable time T. Spin-spin interactions between the ions are engineered via a two-tone laser that couples the internal electronic states of the ions to their ground-state cooled transverse motional modes.

3. The interaction period is split by an echo pulse that cancels site-dependent Stark shifts along z and increases the system's coherence time.



Generation of Spin-Squeezed States



- Measured squeezing vs. interaction time for α ≈ 1, J_0 = 560 rad/s in a 12-ion chain and α ≈ 0.9, J_0 = 216 rad/s in an N = 51 ion chain.
- Black dashed line: Simulated OAT curve with decoherence.
- Black dotted line: Simulated TFI curve with decoherence.
- Black dots: Experimental results.

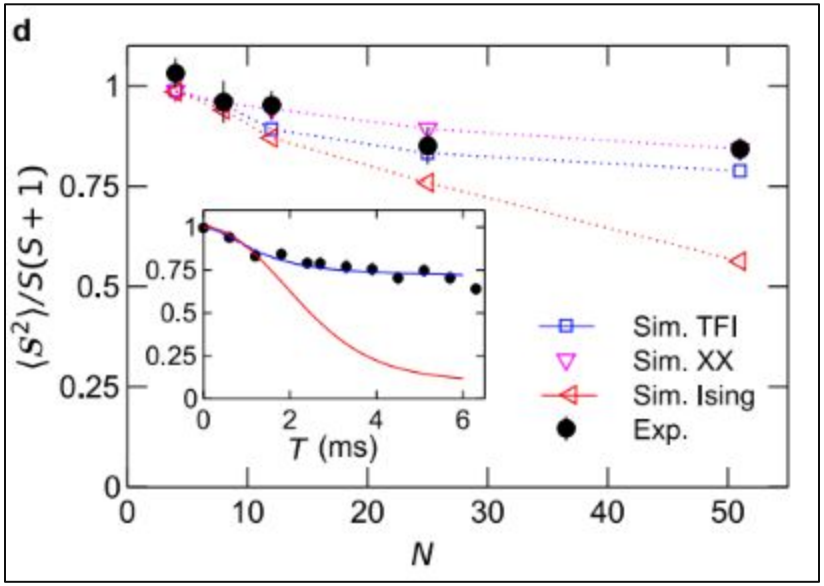
$$\xi^2 = \min_{\mathbf{n}_\perp} \frac{N\left\langle\left(\Delta \hat{S}_{\mathbf{n}_\perp}\right)^2\right\rangle}{|\langle\hat{\mathbf{S}}\rangle|^2}$$

Wineland Parameter

- OAT Model: $\xi^2 \sim N^{-2/3}$.
- Optimal value of $\xi^2 = -3.9 \pm 0.3$ dB for N = 12 ions (α = 1).
- Optimal value of $\xi^2 = -3.7 \pm 0.3$ dB for N = 51 ions (α = 0.9).
- Unexpected reduction in attainable spin squeezing with increased N → Attribute to laser noise & B field fluctuations.
- Similar reduction with OAT model, $\chi = J_{Average}$ & collective dephasing.
- Reduction in spin squeezing is due to factors outside of XX model.

arxiv: 2303.10688, Page 2

Examining <S^2> at Optimal Spin-Squeezing Time



- Total spin, measured at the time at which the spin squeezing peaks in the XX model (interaction strength between 216 and 234 rad/s for all system sizes N), and normalized by its maximal value S(S + 1) for S = N/2.
- Inset: total spin as function of interaction time T for 51 ions, compared to theoretical results for the TFI (blue) and Ising (red) models.

- Total spin operator $\langle S^2 \rangle$ commutes with global dephasing operator → unaffected by it.
- $\langle S^2 \rangle$ decays with larger N, but plateaus to a large value compared to Ising model.
- Observed dynamics over time for N=51 ions: Experimental curve remains much more collective than Ising model.

Spin-wave Excitations (SWE)

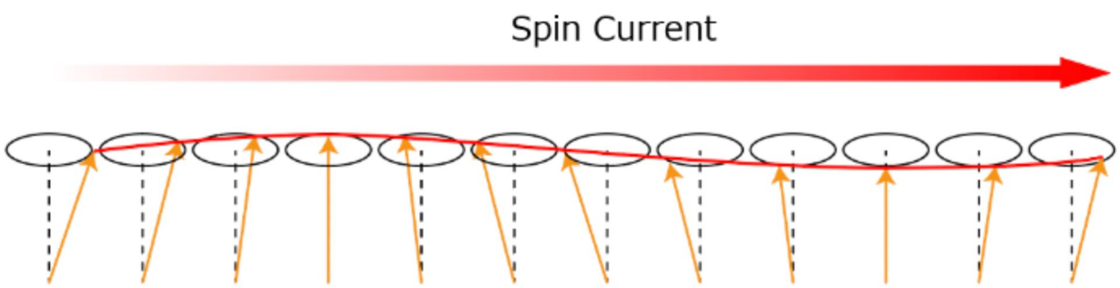


Fig. 1. Schematic of spin waves. Spin oscillations propagate like waves.

Infinite-range Interactions(OAT Model) only k=0 mode

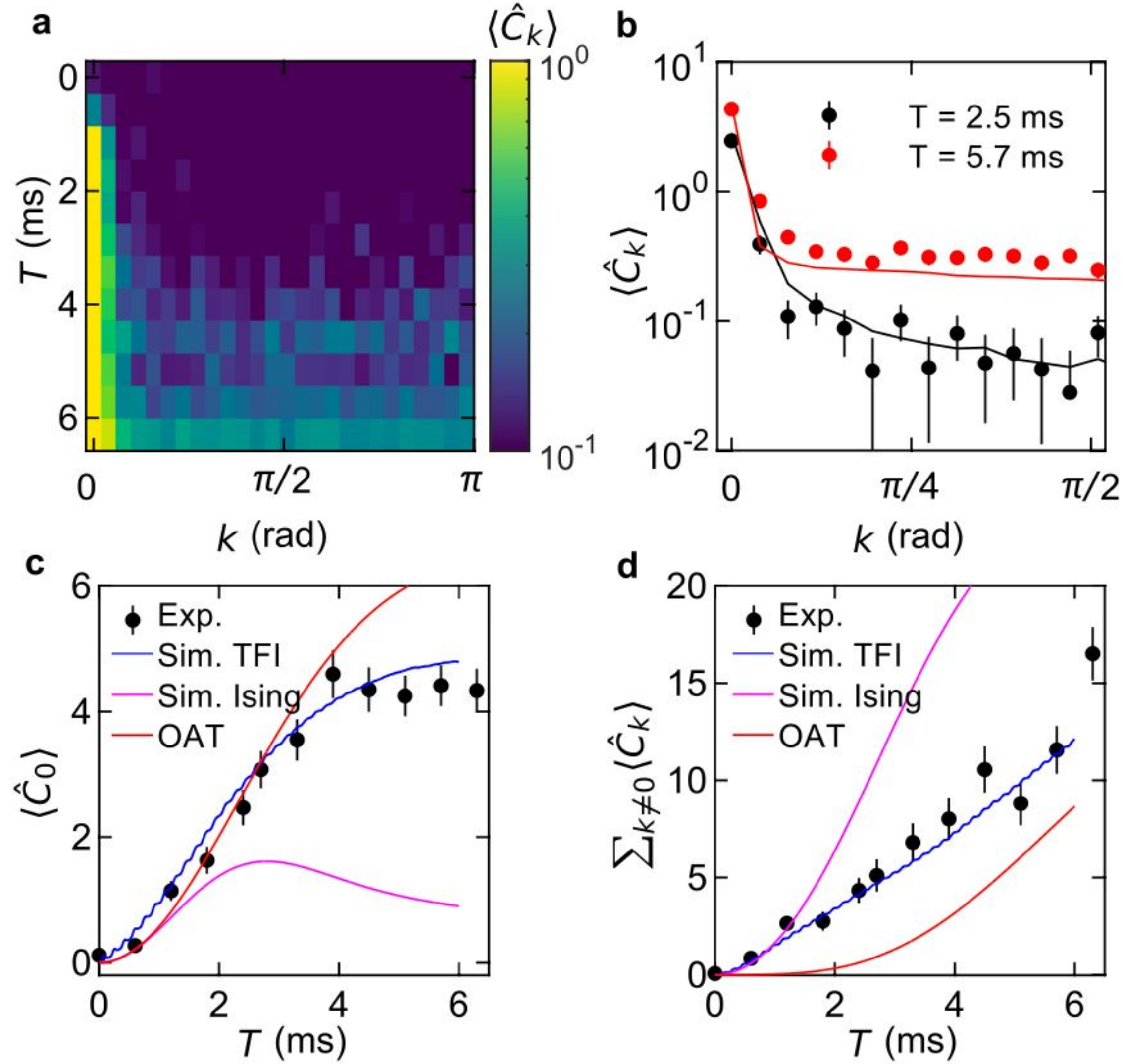
Finite-range Interactions(PL-XX model) finite-wavenumber excitations (k ≠ 0)

Estimate the mode occupation of SWE

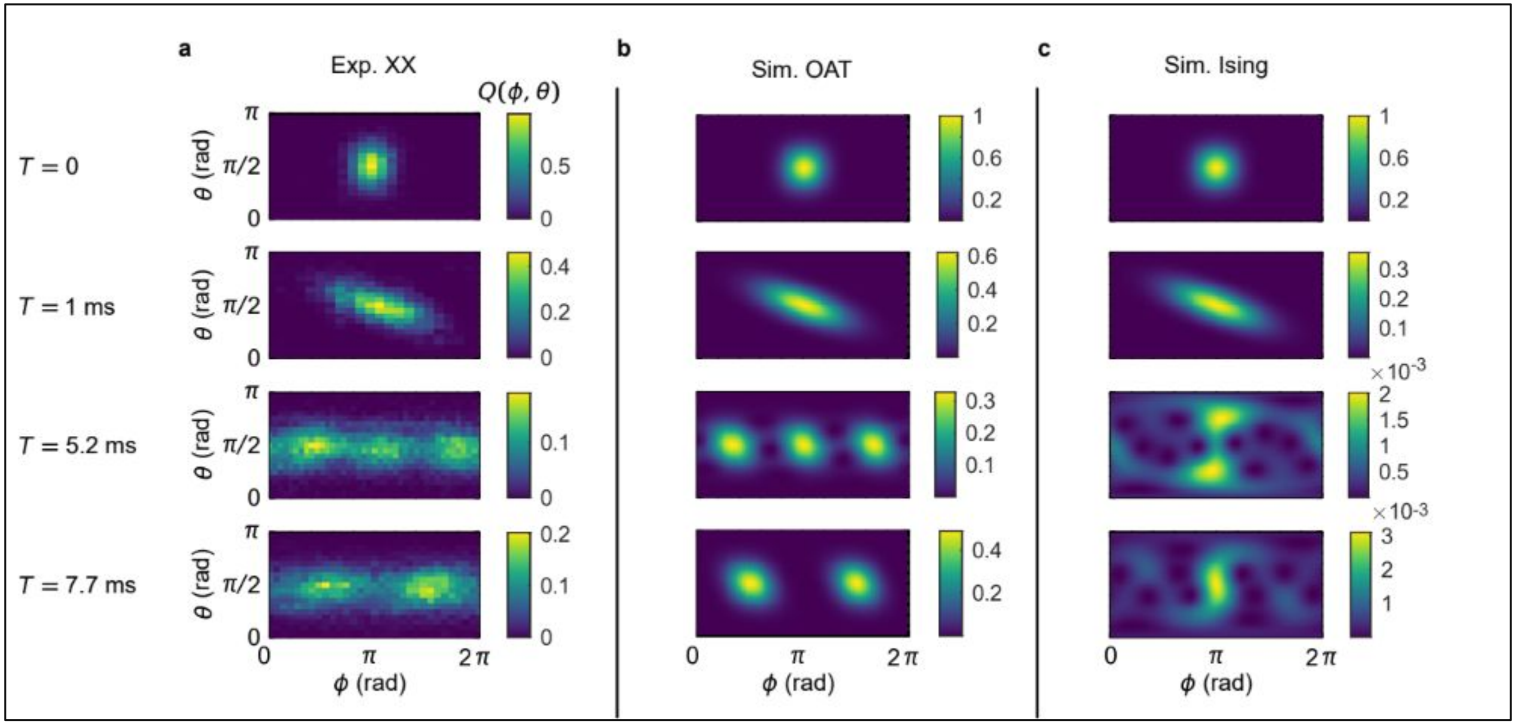
$$\frac{\langle \hat{n}_k + \hat{n}_{-k} \rangle}{2} \simeq \langle \hat{C}_k \rangle \equiv \frac{1}{2} - \frac{1}{2N} \sum_i \langle \hat{\sigma}_i^x \rangle + \frac{1}{2N} \sum_{i<j} \langle \hat{\sigma}_i^y \hat{\sigma}_j^y + \hat{\sigma}_i^z \hat{\sigma}_j^z \rangle \cos(k(r_i - r_j))$$

https://group.ntt/en/newsrelease/2021/12/08/211208a.html

Spin-wave propagation

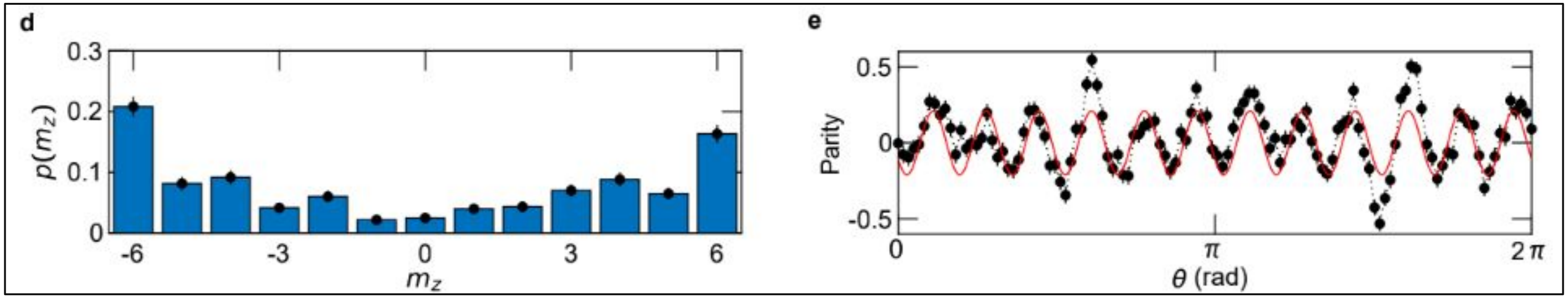


Q-functions: Beyond the Gaussian Regime



- Evolve state past optimal spin squeezing time → non-gaussian states
  - $T = \pi/qJ_{Average}$ → ‘q-headed cat’ states
  - q=2 → GHZ state (maximally entangled)
- Husimi Q-distribution: $Q(\theta,\varphi) = \langle \mathbf{n}(\theta,\varphi)|\varrho|\mathbf{n}(\theta,\varphi)\rangle$
- Clear difference in noise distribution between Ising and OAT model simulations

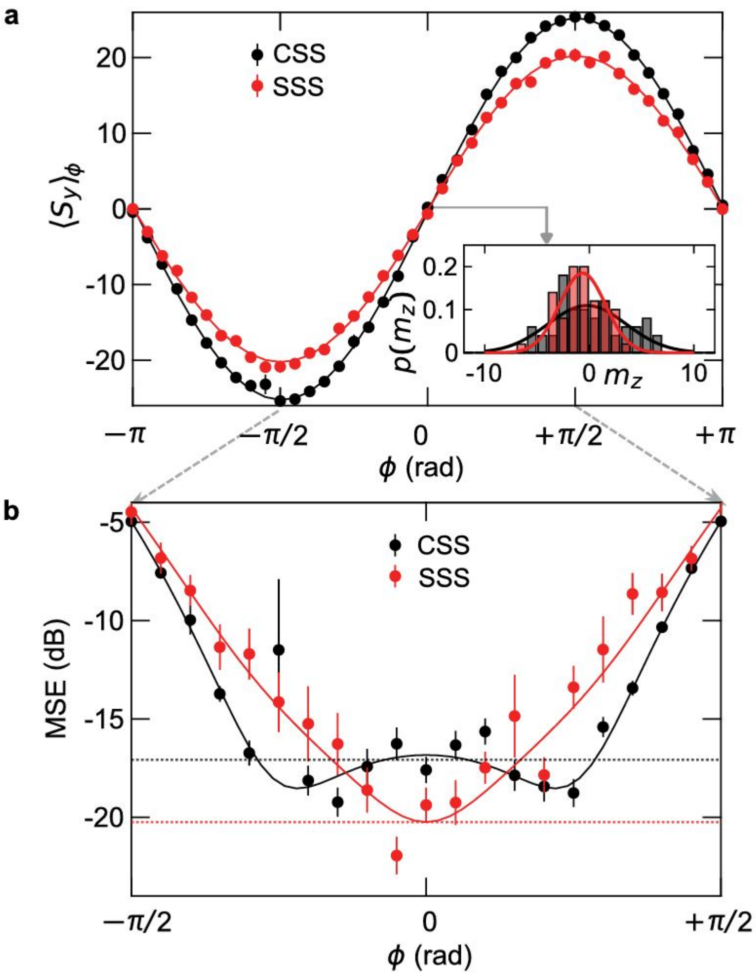
Measuring Coherence of the GHZ State

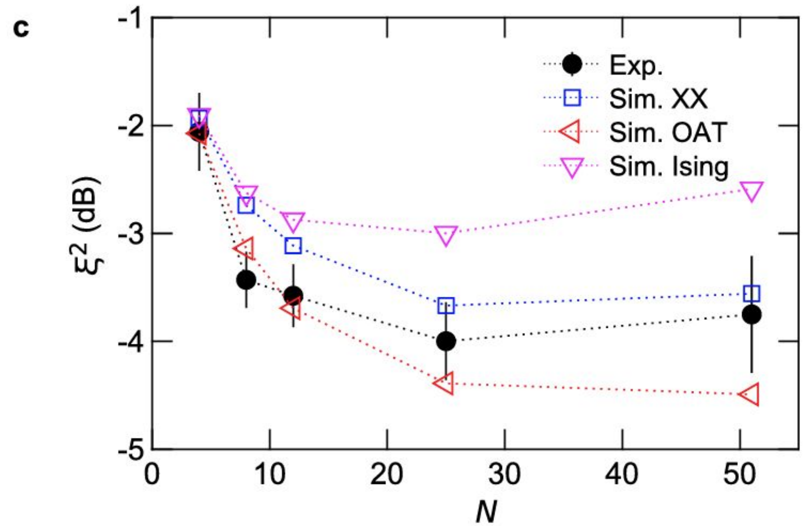


d) Measured probabilities in all magnetization sectors $m_z = (n_\uparrow - n_\downarrow)/2$ of the 2-headed cat state. Here $n_{\uparrow(\downarrow)}$ is the number of ions in the state $|\uparrow\rangle(|\downarrow\rangle)$. e) Parity oscillations of 2-headed cat state and corresponding sinusoidal fit in red to estimate the contrast C. The black dotted line is a guide to the eye.

- For useful GHZ state, coherence must be present between each CSS state in the superposition
    - Perform parity oscillations
    - Projecting state into $|\pm N/2\rangle$eigenstates of S_z and measuring m_z → calculate fidelity
    - $F = [p(m_z = +N/2) + p(m_z = -N/2) + C]/2$.
- Found F = 0.28 ± 0.2 (F =0.5 required to certify N-partite entanglement)
- Without decoherence, expect up to F = 0.916 (12 ions)
- Ising model can only achieve up to F < 0.002 for q-headed cat states

Phase Estimation





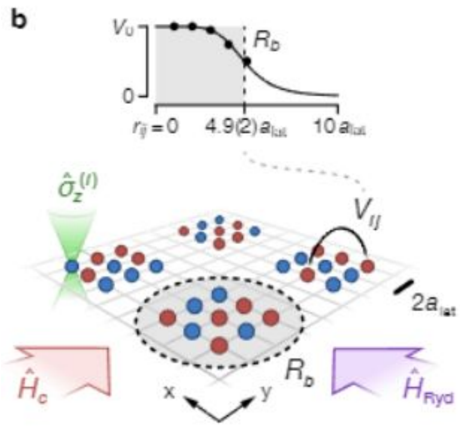
a. Experimental Ramsey fringes as a function of φ.
b. Mean squared error between imprinted and estimated phases as function of φ.
c. ξ^2 (Wineland Parameter) as a function of the number of ions for the various models.

Conclusion

- Utilizing short-range interactions to achieve collective behavior is an important step towards scaling quantum sensors and clocks

- This concept can be applied to systems of higher spatial dimensionality with better protection expected

- The simple protocol paves the way for advances in time-keeping and new methods for preserving coherence in quantum simulation and computation.



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Appendix: Parity Oscillations

$$R(\tilde{\theta}, \tilde{\phi}) = \prod_j e^{-i\frac{\tilde{\theta}}{2}(\sigma_j^x \cos\tilde{\phi} + \sigma_j^y \sin\tilde{\phi})},$$

Rotation by theta about an axis on the equator parameterized by phi

$$\sum_{m_z} e^{-i\pi(S+m_z)} \left|\langle m_z| R(\pi/2, \tilde{\phi}) |\text{cat}\rangle\right|^2.$$

Evaluation of Parity