Quantum simulation and sensitive force detection using hundreds of trapped ions

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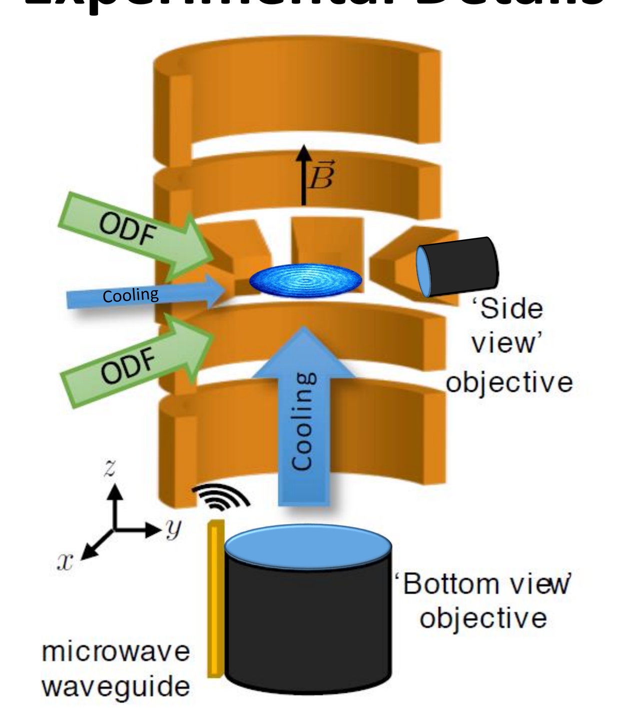
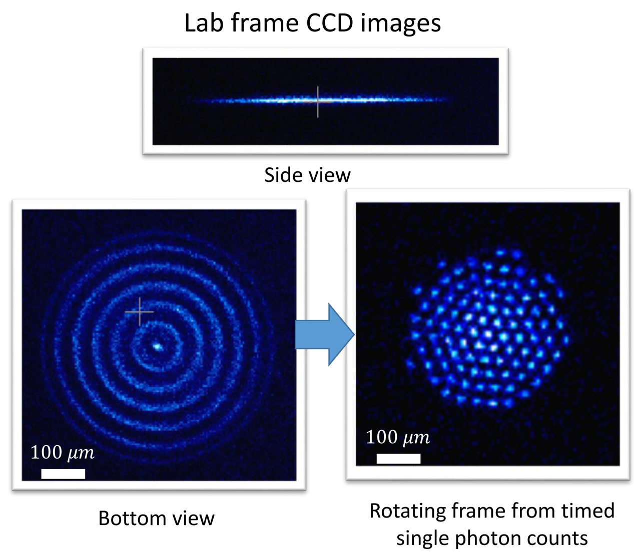
NIST Ion Storage

Motivation

Systems of trapped ions have made substantial progress as simulators of quantum magnetic models. But increasing a simulator's complexity by controlling more than 30 ions is an outstanding challenge. Here we perform quantum simulations of long range Ising spin models far from equilibrium using hundreds of beryllium ions in a Penning trap. We benchmark the fidelity of the quantum simulator by producing entangled states in planar arrays of ions, directly observing spin-squeezed states with up to 6.0 dB of spectroscopic enhancement. We show how the ability to time-reverse the spin dynamics allows for tracking the spread of quantum information through the system by measuring out-of-time-order correlation functions. To study the stability of the center-of-mass mode of the ions, one of the limitations to our simulations, we use the spin-motion coupling of the ions to sense small electric fields that induce amplitude displacements as small as 50 pm, 40 times small than the center-of-mass mode zero-point fluctuations.

Experimental Details



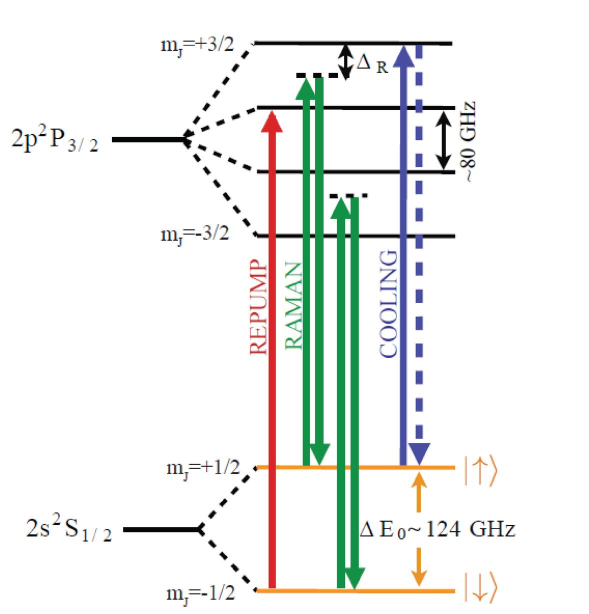


Bottom view

Rotating frame from timed single photon counts

Key parameters:
Magnetic field $B = 4.46\ T$
Axial freq. $\omega_z = 2\pi \times 1.57$ MHz
Rotation freq. $\omega_r = 2\pi \times 180$ kHz (single plane)
Magnetron freq. $\omega_m = 2\pi \times 161$ kHz
Cyclotron freq. $\Omega_c = 2\pi \times 7.6$ MHz

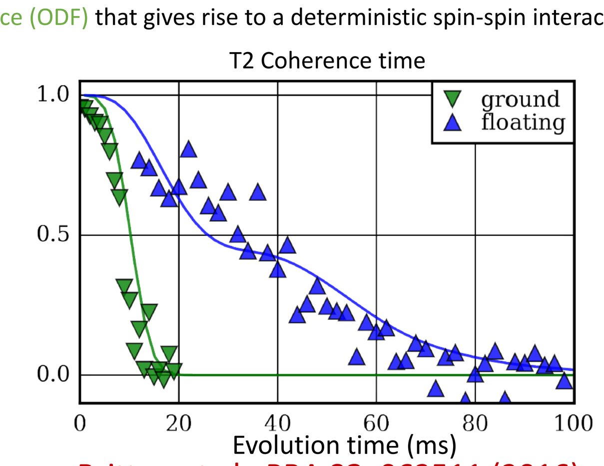
$^9Be^+$ qubit system



High field qubit – Our qubit is the $^9Be^+$ valence electron spin. In a 4.46 T magnetic field the qubit splitting is 124 GHz. Global single qubit rotations are obtained from a 124 GHz microwave source at a Rabi rate of $2\pi \times 10$ kHz.

Near-resonant cooling laser beams at 313 nm prepare an ion crystal at the Doppler limit (~ 0.5 mK) and permit qubit state discrimination by resonance fluorescence.

Far-detuned laser beams generate a spin-dependent optical dipole force (ODF) that gives rise to a deterministic spin-spin interaction.



Britton et al., PRA **93**, 062511 (2016).

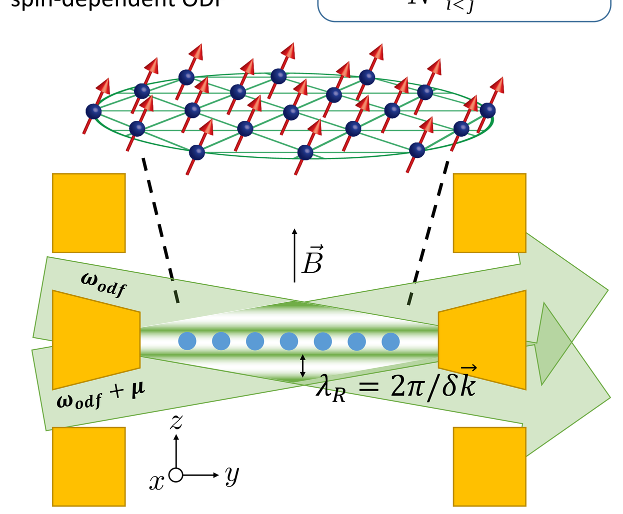
Ising interaction with spin-dependent force

Two far-detuned laser beams produce a spin-dependent optical dipole force (ODF) at the ions that gives rise to a **spin-spin interaction**. Combined with a transverse magnetic field, we can realize non-trivial quantum magnetic interactions.

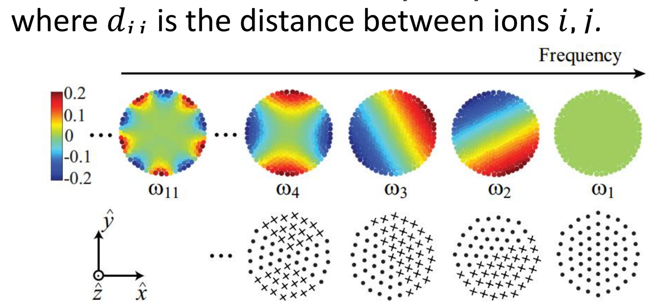
Transverse B-field from 124 GHz microwaves $\Rightarrow$ $H_B = B_x \sum_i \hat{\sigma}_i^x$

Engineered Ising interaction from spin-dependent ODF $\Rightarrow$ $H_I = \frac{1}{N} \sum_{i<j} J_{i,j} \hat{\sigma}_i^z \hat{\sigma}_j^z$

Coupling to different axial modes allows for a **tunable interaction range** $J_{ij} \propto d_{ij}^{-\alpha}, \alpha \in [0,3]$ where d_{ij} is the distance between ions i, j.



$F_\uparrow(t) = -F_\downarrow(t) = F_0 \cos(\mu_R t)$



$$J_{i,j} = \frac{F_0^2 N}{2\hbar M} \sum_{m=1}^{N} \frac{b_{i,m} b_{j,m}}{\mu_R^2 - \omega_m^2}$$

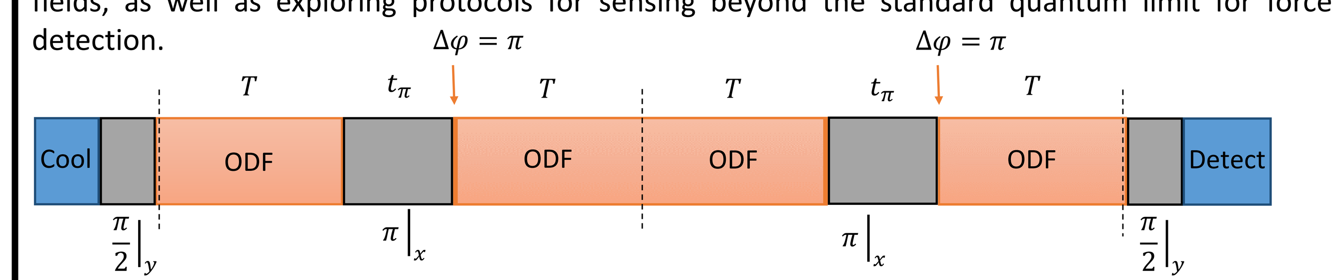
Spin-spin interaction

For α<<1: $J_{i,j} \approx \bar{J} = \frac{F_0^2}{4M\omega_z\delta}$

Picometer-scale displacement sensing

Gilmore, et al, In Progress.

A spin-dependent optical dipole force couples the ions' spin to their motion. Similar to cavity optomechanics experiments, this coupling transduces the motion of the mechanical oscillator – the center-of-mass (COM) mode of the 2D ion crystal – to a qubit frequency shift. This shift in the qubit frequency manifests as spin precession, which we measure. Here, the COM motion is sensed phase-incoherently with respect to the spin-dependent force. For motion off-resonant with the trap axial frequency we demonstrate measurements of amplitudes 40 times below the ground state zero-point fluctuations (2 nm for 100 ions). Phase coherent detection with this set-up can achieve a sensitivity of 20 pm/$\sqrt{\text{Hz}}$ which will be useful for detecting extremely weak forces and electric fields, as well as exploring protocols for sensing beyond the standard quantum limit for force detection.



Experimental sequence. Phase shifts allow for coherent accumulation of spin precession.

Apply calibrated voltage to endcap electrode to drive ion motion:

$$\hat{z}_i \to \hat{z}_i + Z_c \cos(\omega t + \delta)$$

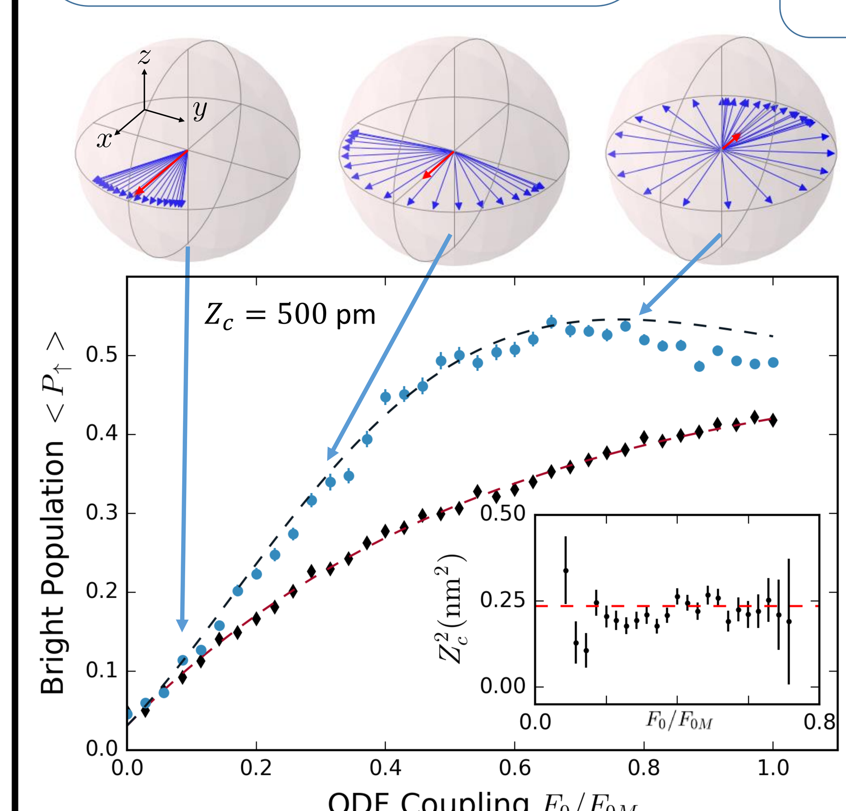
$$H_{ODF} \cong F_0 \cdot Z_c \cos[(\omega - \mu)t + \delta] \sum_i \frac{\hat{\sigma}_i^z}{2}$$

Qubit frequency shift: $\Delta(Z_c) = \left(\frac{F_0}{\hbar}\right) Z_c \cos(\delta)$
Precession angle: $\theta = \Delta\,\tau \equiv \theta_{max}\cos(\delta)$

Probability of measuring spin up:

$$\langle P_\uparrow \rangle = \frac{1}{2}\left(1 - e^{-\Gamma\tau}\langle\cos\theta\rangle\right)$$

$$\langle\cos\theta\rangle = J_0(\theta_{max})$$



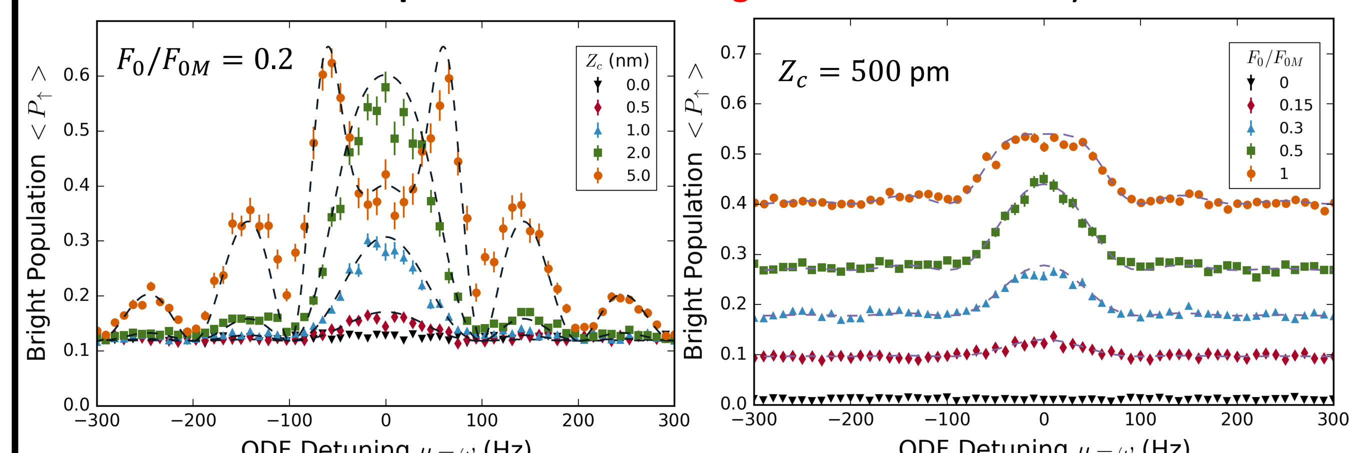
Axial motion leads to spin dephasing

Vary measurement strength:

- **Background (black)** explained by spontaneous emission model
- Signal due to **driven motion (blue)** well modeled by theory

Inset: Extract Z_c^2. **Signal to noise** goes through a maximum.

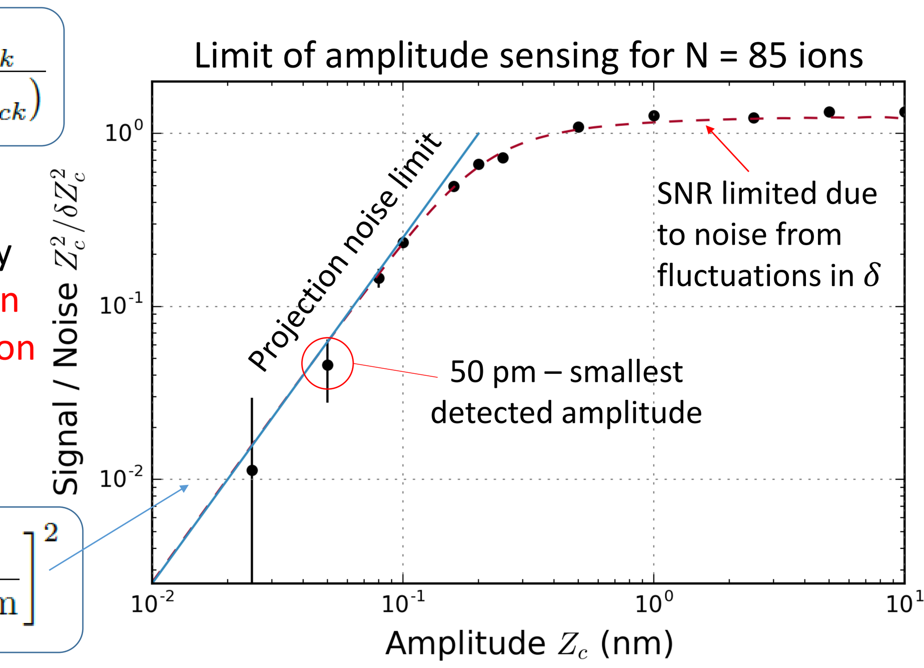
Lineshape shows excellent agreement with theory



$$\frac{Z_c^2}{\delta Z_c^2} \approx \frac{\langle P_\uparrow \rangle - \langle P_\uparrow \rangle_{bck}}{\delta\left(\langle P_\uparrow \rangle - \langle P_\uparrow \rangle_{bck}\right)}$$

Sensitivity limited by spontaneous emission and quantum projection noise

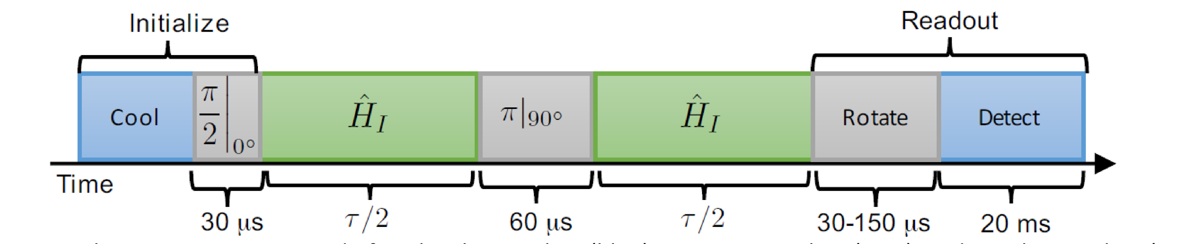
$$\frac{Z_c^2}{\delta Z_c^2}\bigg|_{limiting} = \left[\frac{Z_c}{0.2\ \text{nm}}\right]^2$$



Spin squeezing and entanglement

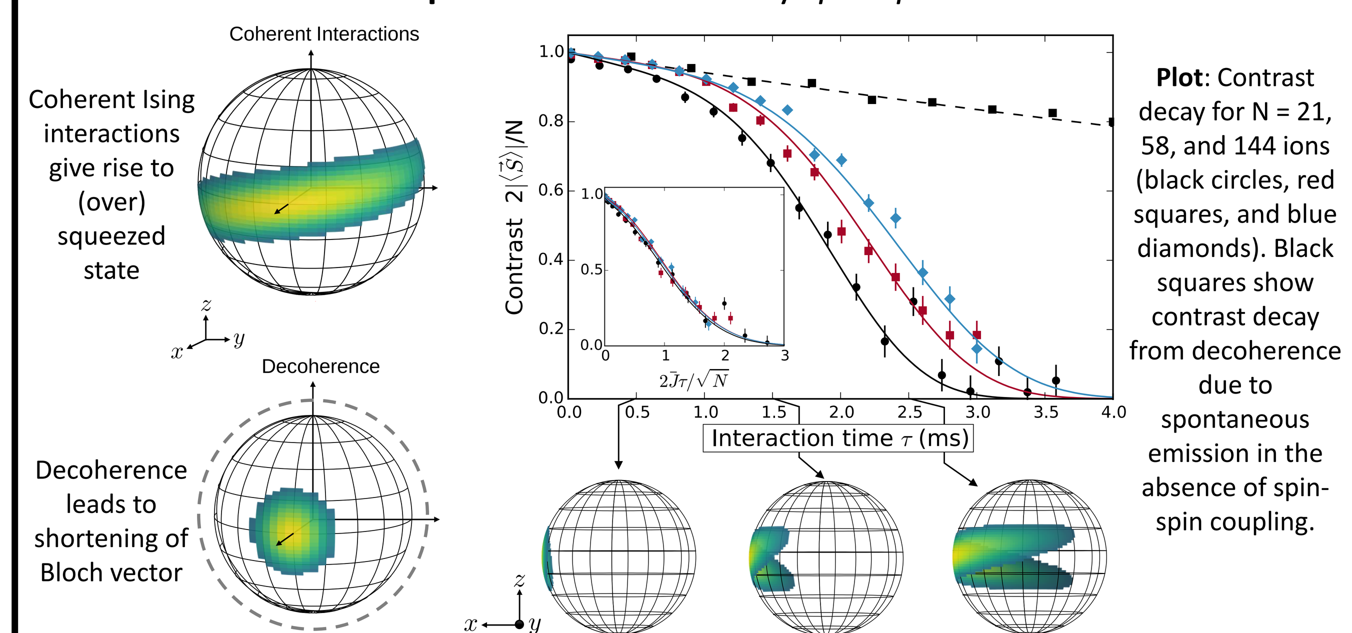
Bohnet, et al, Science **352**, 1297 (2016).

We use spin squeezing as a benchmark of quantum correlations in the spin ensemble. The coherent Ising interaction in the presence of decoherence from spontaneous emission requires theory for the many-body physics of an open quantum system. To benchmark entanglement experimentally, we measure both the reduction in the average collective spin component $\langle S_x \rangle$, equivalent to the Ramsey fringe contrast, and collective spin variance $(\Delta S_\psi)^2$. These measurements can be combined to form an entanglement witness with the Ramsey squeezing parameter ξ_R^2.



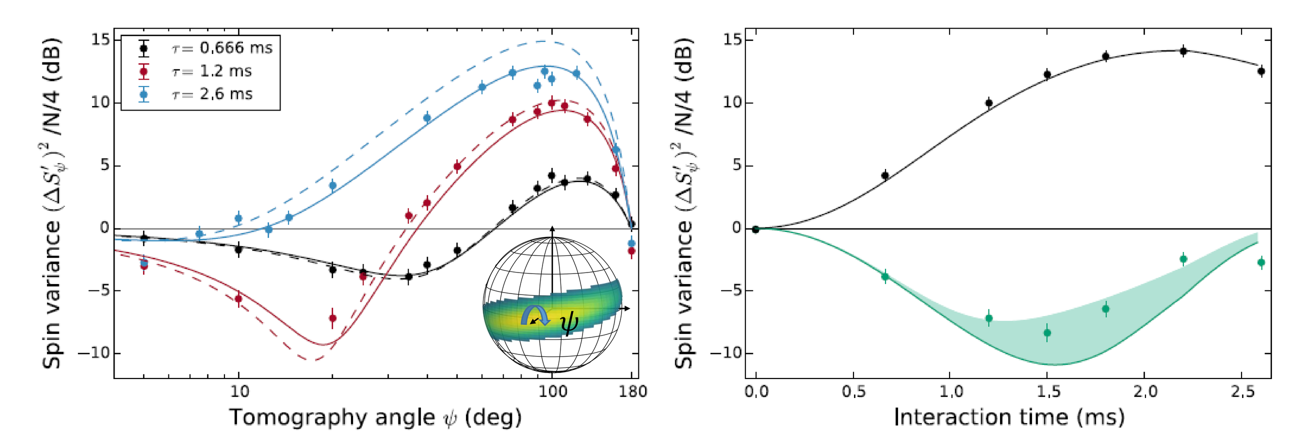
Experiment pulse sequence, composed of cooling laser pulses (blue), microwave pulses (grey), and ODF laser pulses (green).

Observe depolarization of the collective spin.
Distinguish destruction of correlations caused by *decoherence* from **coherent depolarization** caused by *spin-spin interaction*.



Plot: Contrast decay for N = 21, 58, and 144 ions (black circles, red squares, and blue diamonds). Black squares show contrast decay from decoherence due to spontaneous emission in the absence of spin-spin coupling.

Measure and benchmark modification of collective spin variance and **verify entanglement** using spin-squeezing.



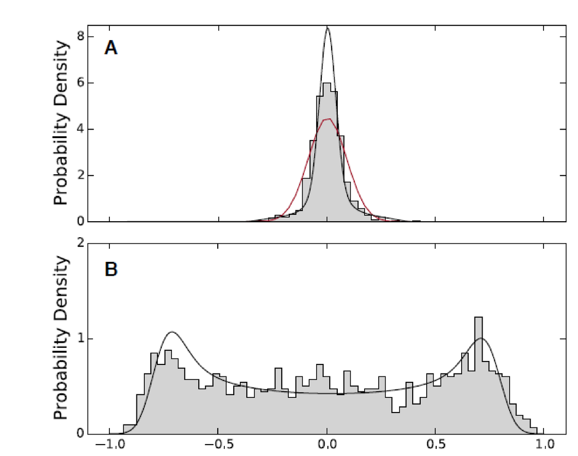
Depolarization combined with spin variance allows us to evaluate the entanglement witness.

Entanglement witness: $\xi_R^2 = N \frac{min_\psi[(\Delta S_\psi)^2]}{|\langle\vec{S}\rangle|^2}$ entangled when: $\xi_R^2 < 1$

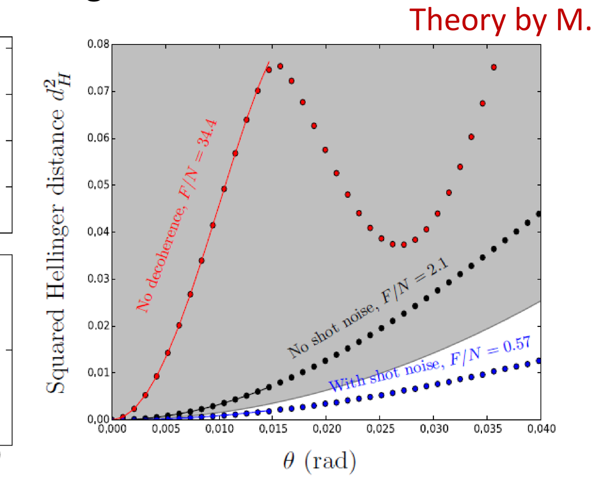
Maximum observed squeezing of **-6.0 dB** with 88 ions.
Entanglement observed for N from **20 to 220 ions**.

Observe non-Gaussian counting statistics in collective spin state.
Disappearance of spin-squeezing at long times consistent with formation of **over-squeezed state** - not just degradation due to decoherence.

Theory by M. Wall



Full counting statistics of a non-Gaussian spin state. Histograms showing the (A) squeezed and (B) anti-squeezed quadratures of the collective spin.



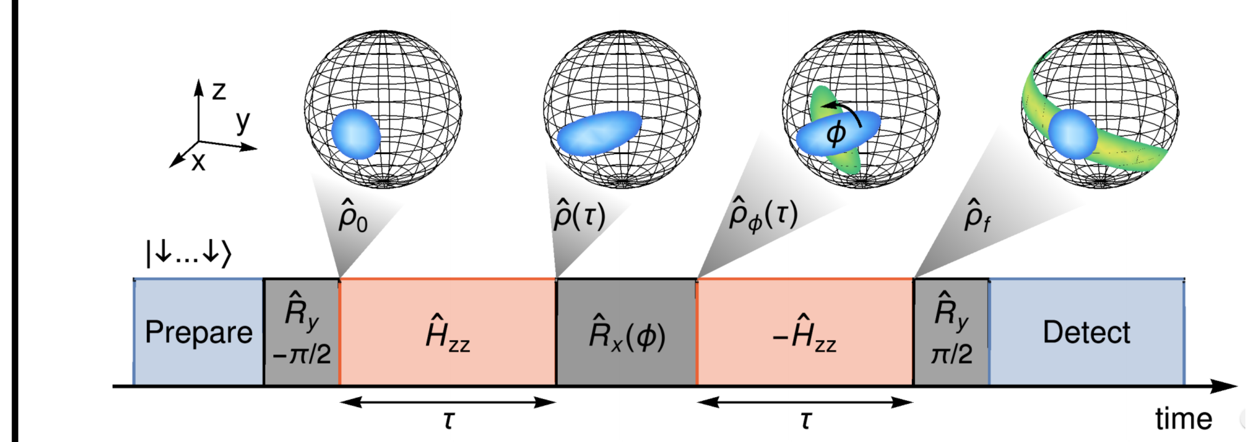
Fisher information (F) is extracted from theoretically computer Hellinger distance. F/N > 1 indicates the state is entangled.

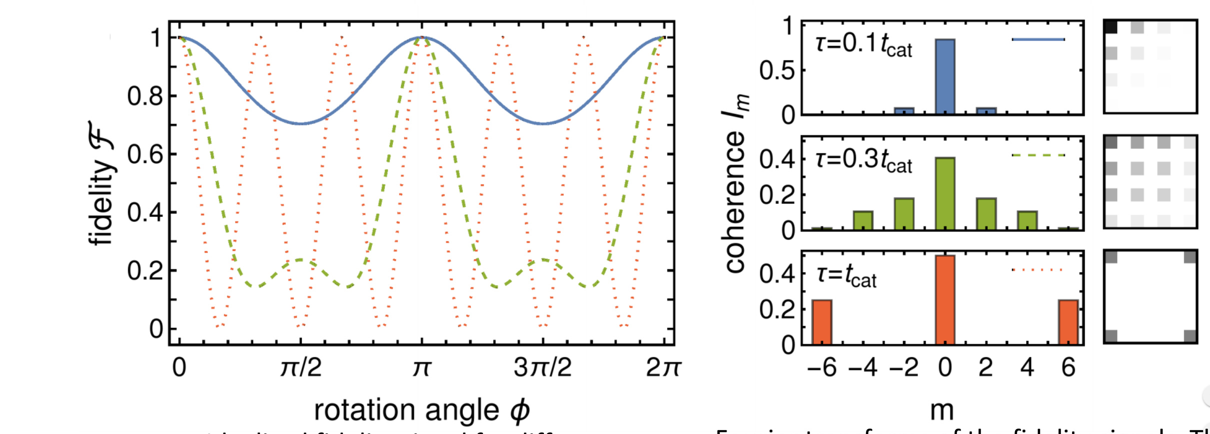
Multiple quantum coherences

Gärttner, et al, **arXiv:1608.08938**.

Probing coherence and entanglement of quantum states with many-body echoes as in multiple quantum NMR (Baum, et al, J. Chem. Phys. (1985)) is useful for benchmarking quantum simulators and studying dynamics of higher order correlations. The multiple quantum coherence (MQC) protocol implements the measurement of an out-of-time-order correlation (OTOC) function. Experimental implementation involves time reversing the engineered Ising interaction, which is done by inverting the sign of J_{ij}.

Overlap with initial state as a function of rotation angle yields **oscillations** from which the multiple quantum **coherences** are obtained.

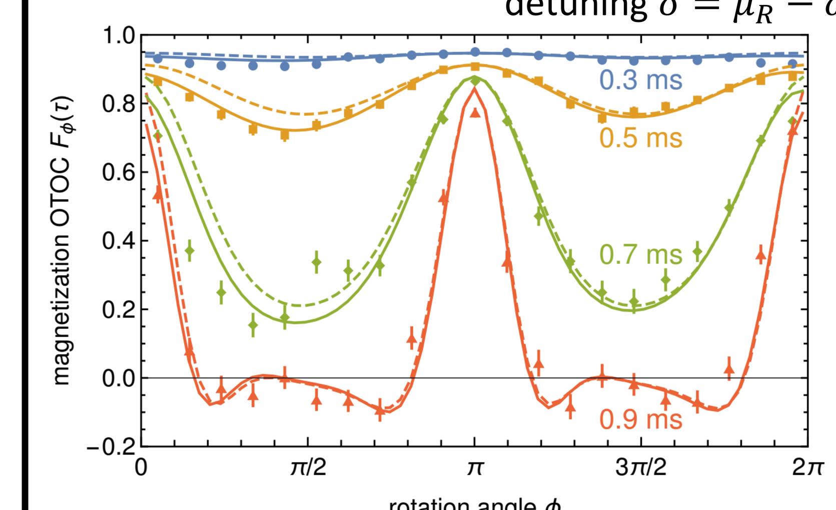




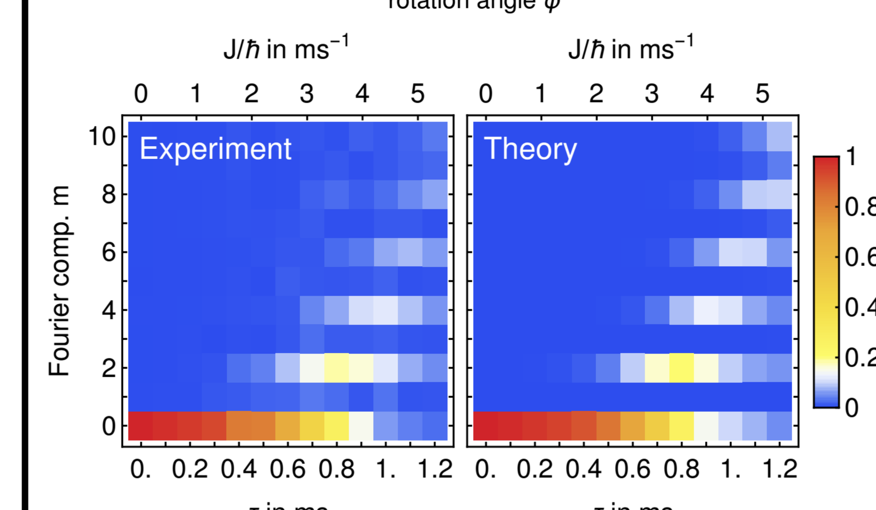
Idealized fidelity signal for different evolution times τ.

Fourier transforms of the fidelity signals. The Fourier amplitudes are identical with the multiple quantum coherences.

We **experimentally** control the sign of the Ising interaction ($J \sim 1/\delta$) by shifting the frequency of the ODF beatnote μ_R, changing the sign of the detuning $\delta = \mu_R - \omega_z$.



Experimental measurement of $\langle S_z \rangle$ as a function of rotation angle serves as a **benchmark** of quantum simulator.



Experimentally measured Fourier components of $\langle S_z \rangle(\phi)$ show excellent agreement with theory, reflecting the **buildup of many-body correlations.**

MQC spectrum shows time dynamics of many-body correlations. As an **OTOC measurement**, shows scrambling of information: information stored in initial state is distributed, through interactions, over many-body degrees of freedom.

Future Directions

- Transverse magnetic field, with variable range spin-spin interactions
- Phase coherent sensitive force detection
- Apply sub-Doppler cooling (EIT) to the axial drumhead modes
- Implement single-ion resolved readout