FY25 Strategic University Research Partnership (SURP)

Quantum Entanglement and Squeezing in Atomic Systems for Space Applications

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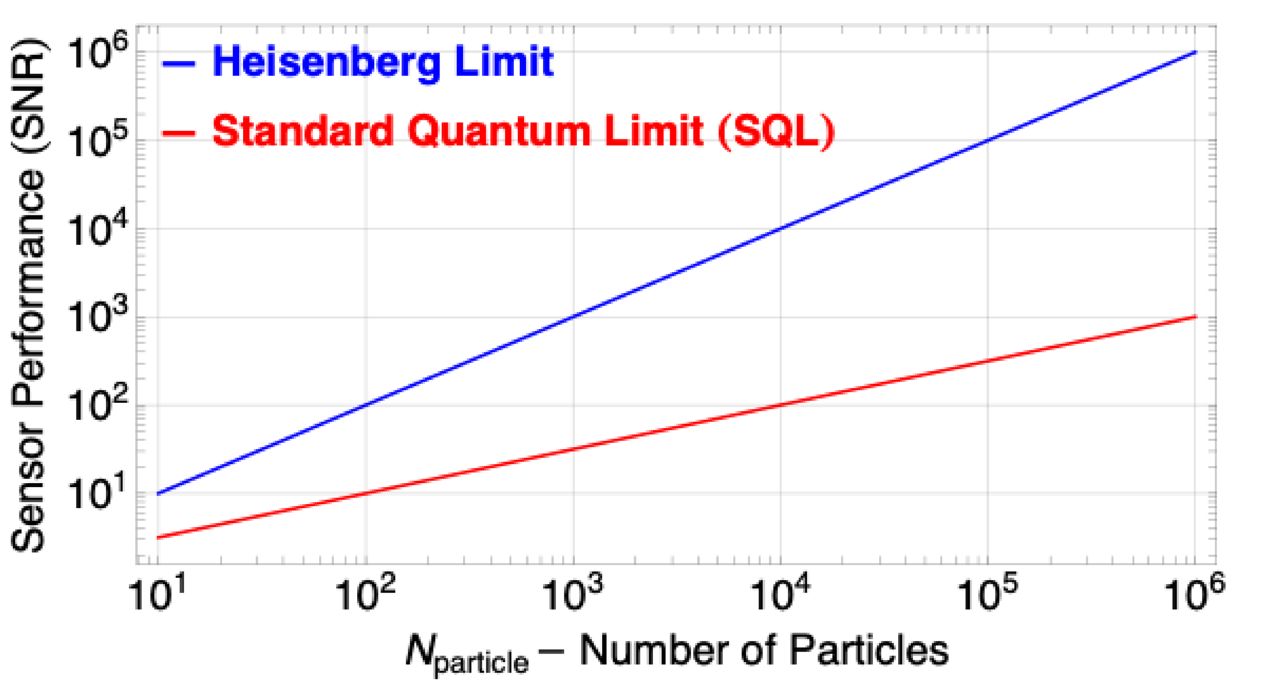
Objectives: This proposal aims to take advantage of quantum spin squeezing and entanglement of an atomic system to improve the sensitivity of atom-based quantum sensors. A simple and robust method is key to enabling quantum sensors for space applications. Here we will develop a feasible approach to generate squeezing and entanglement that can be implemented in the compact atom-based quantum sensors at JPL, such as the atomic clock, atom interferometer, atomic gyroscope, and magnetometer.

Background

- A traditional quantum sensor uses a quantum coherent state to make sensing measurements. The sensor sensitivity is typically limited by the standard quantum limit as $1/\sqrt{N_{particle}}$.
- An entangled squeeze state can suppress the measurement noise below the standard quantum limit, reaching the Heisenberg limit of $1/N_{particle}$.
- An entangled squeeze state can improve quantum sensor performance beyond the SQL limit.



Approach and Results

- We will generate an entangled squeeze state using **atomic spin-1 Bose-Einstein condensates**.
- The spin interaction induces the spin mixing in spin-1 BEC
$$|{+1}\rangle + |{-1}\rangle \rightleftharpoons |0\rangle + |0\rangle$$
- The Hamiltonian of quantum system is described by the spin-spin interaction and Zeeman energy as [1],
$$\hat{H} = \lambda_s \hat{S}^2 + \frac{q_B}{2}\hat{Q}_{zz}$$

Here λ_s is the spin interaction energy of the condensate and q_B is the quadratic Zeeman energy. $\hat{S}$ is the spin operator and $\hat{Q}_{zz}$ is the spin-1 quadrupole tensor operator. Entangled squeezed states can be generated from the Hamiltonian evolution of the spin-1 BEC.

- We will investigate different approaches to generate quantum squeezing and entanglement for quantum sensors at JPL. Promising approaches include generating spin squeezing for a large BEC in a single-focus optical dipole force trap.

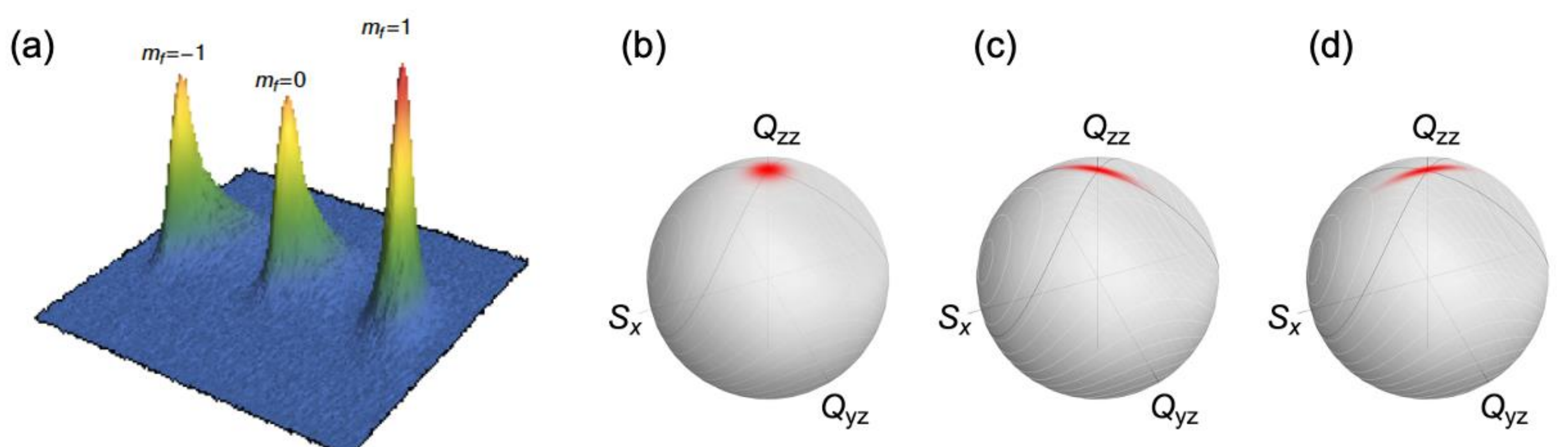


Figure 1. Preparing squeezed state for metrology applications. (a) Image of a spin-1 Bose-Einstein condensate with three spin component, $|m_f\rangle = -1, 0, +1$. (b) The initial state (red shaded area) is prepared where all the atoms are in the $|m_f\rangle = 0$ state, as shown on the $S_x Q_{yz} Q_{zz}$ spin-nematic Bloch sphere. (c) The Hamiltonian squeezes the initial state, and subsequently the state distribution will have a lower uncertainty along the squeezing axis. (d) The squeezed state is rotated to an appropriate direction for a metrology application.

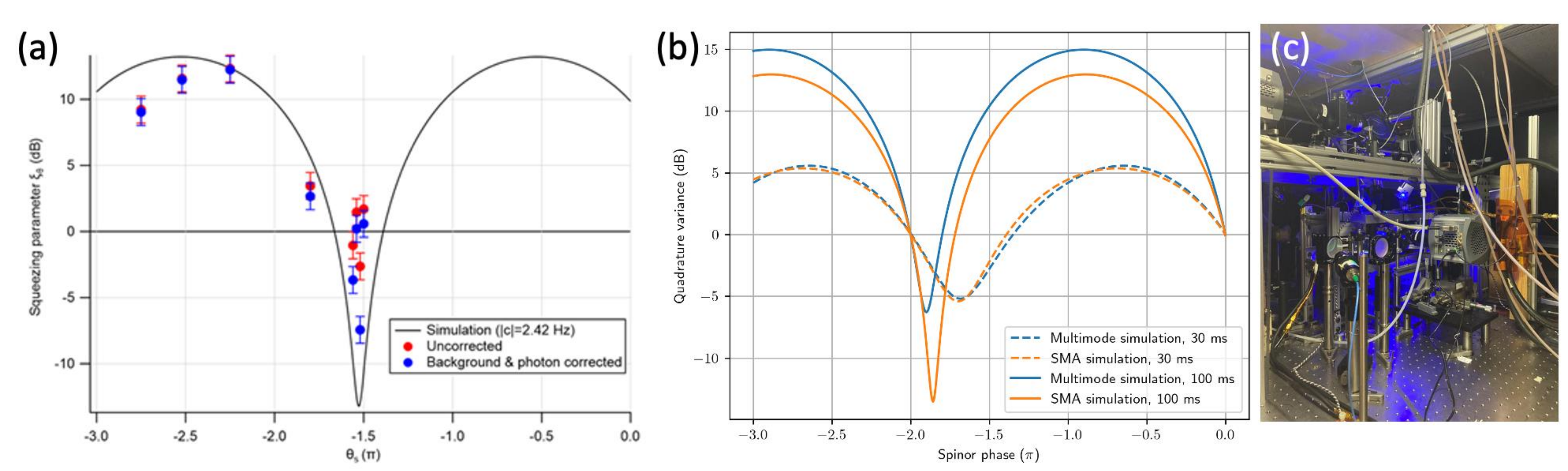


Figure 2. Generate entangled squeezed states in a single-focus Bose-Einstein condensate (BEC) (a) Experimental observation of -3 dB spin squeezing in BEC in a single-focus optical dipole force trap. (b) Generalized spin squeezing simulation beyond the single mode approximation (SMA) in a 1D potential box. (c) Experimental setup.

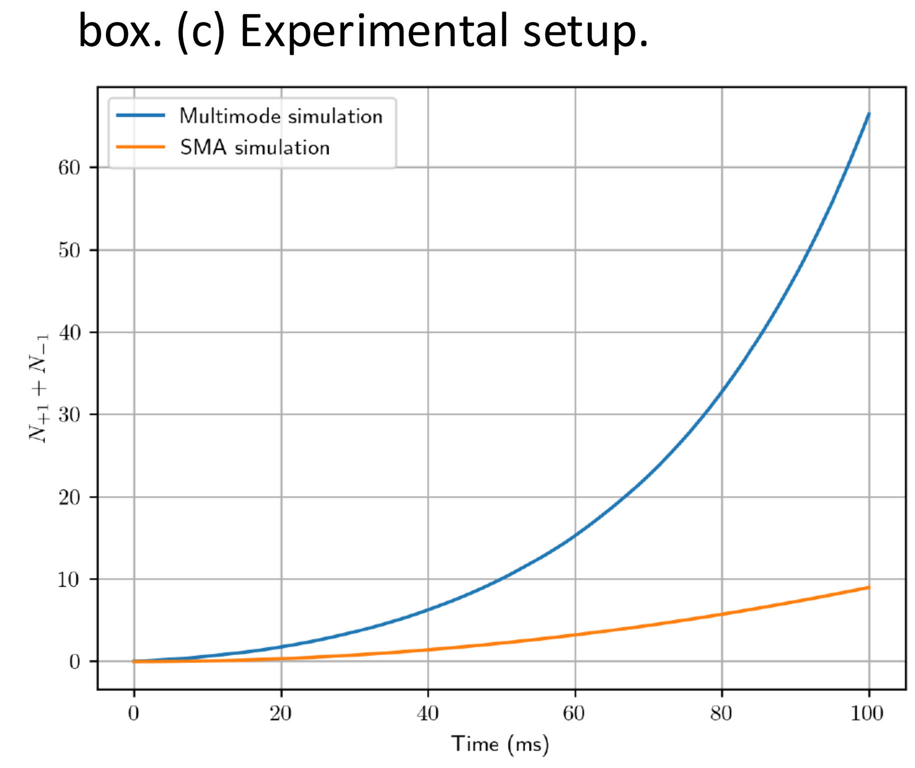


Figure 3. Comparison of the multimode (blue) and SMA (orange) simulations in a 1D potential box.

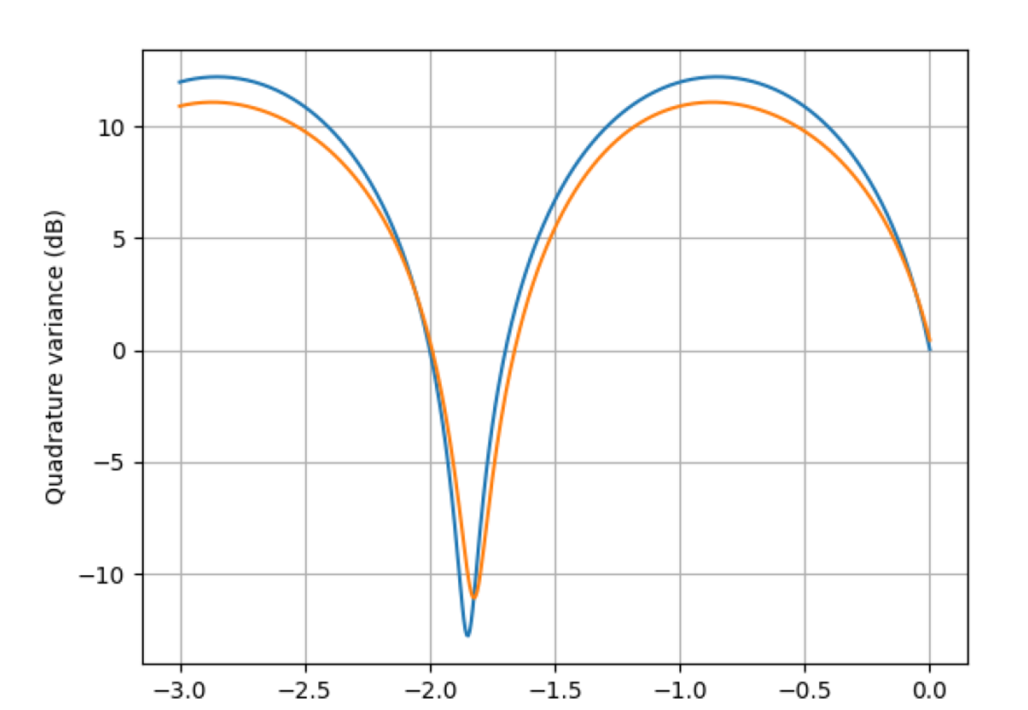


Figure 4. Spin squeezing simulation for multimode (blue) and SMA (orange) in a 1D harmonic trap potential.

Significance/Benefits to JPL and NASA

- A feasible approach for atomic squeezing will have practical benefits for JPL's cold atom-based quantum sensors such as strontium lattice atomic clock, quantum gravity gradiometer (QGG), accelerometers, seismometers, gyroscope, and magnetometer. This new class of quantum sensors can open new science opportunities.
- Quantum-enhanced sensors using spin squeezing and entanglement will revolutionize the quantum sensor technology not only at JPL but everywhere.
- This seed effort will provide us with an opportunity to collaborate and seek new opportunities in the future.

Publications: None

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