Generation of Motional Squeezed states for Atoms in Optical Tweezers

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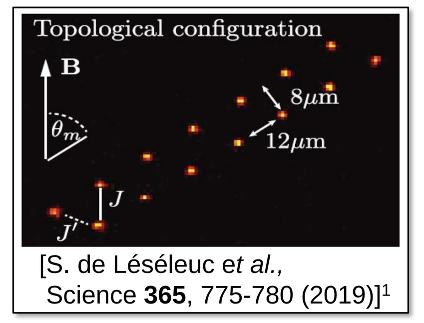
moonshot Goal 6 大森 PM 大規模・高コヒーレンスな動的原子アレー型・誤り耐性量子コンピュータ

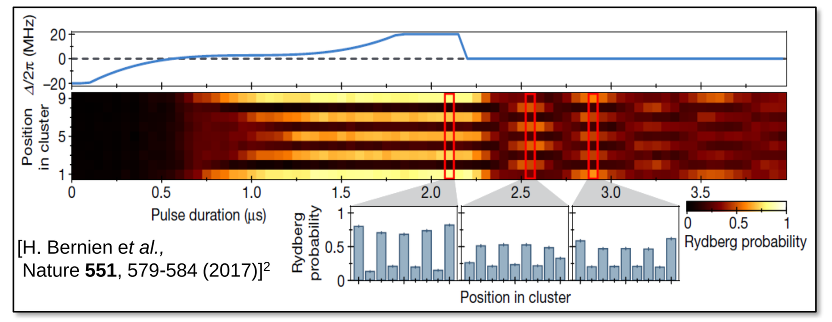
Introduction

Rydberg quantum simulator

- Strong long-range interaction (few μm)
- Tunability of interaction strength
- Rydberg blockade



[S. de Léséleuc et al., Science **365**, 775-780 (2019)][1]

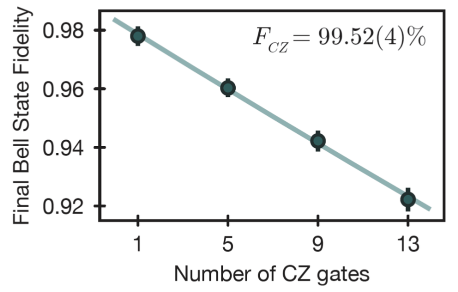


[H. Bernien et al., Nature **551**, 579-584 (2017)][2]

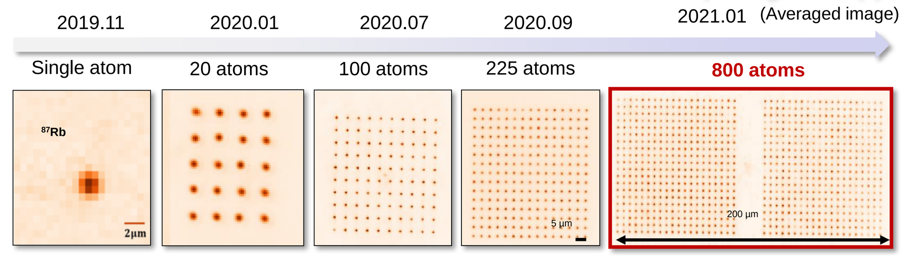
Ising quantum spin model simulation

A promising platform for quantum computing

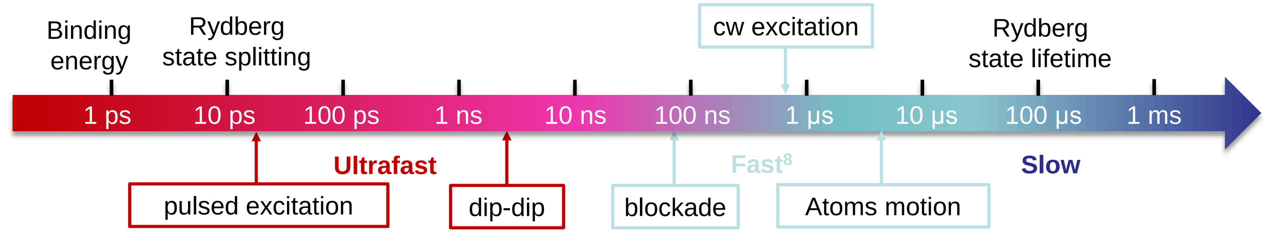
- Long coherence times (one second for T_1)
- Gate fidelity improvements[3]
- Good scalability (800+ atoms achieved)



Final bell state fidelity as a number of 2-qubit gates applied[3]



Ultrafast Rydberg experiments:

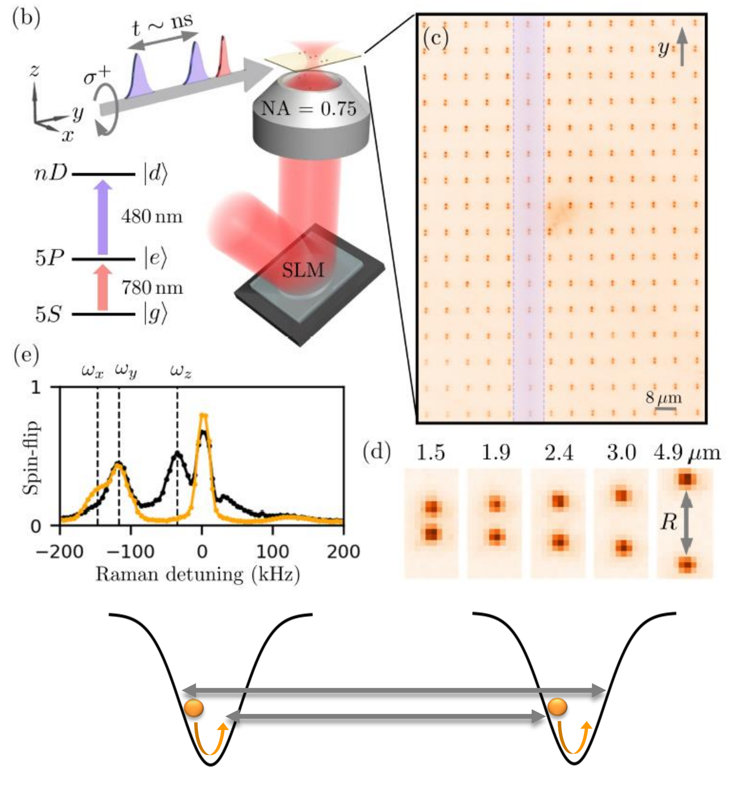


Context and experimental setup

Experimental setup

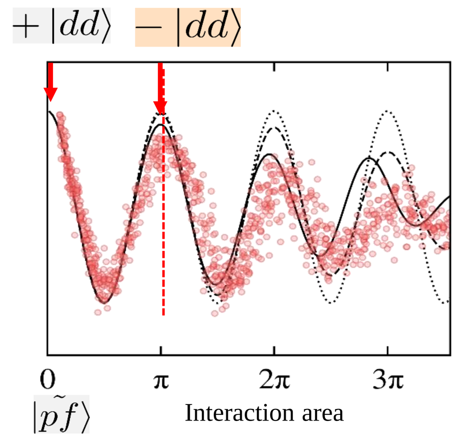
- Microscope with high-NA objective lenses
  - Large atomic arrays with optical tweezers
  - Spatial Light modulator (SLM).
  - Observe and control the atoms with single-site resolution
  - Raman sideband cooling and spectroscopy

Ultrafast gates

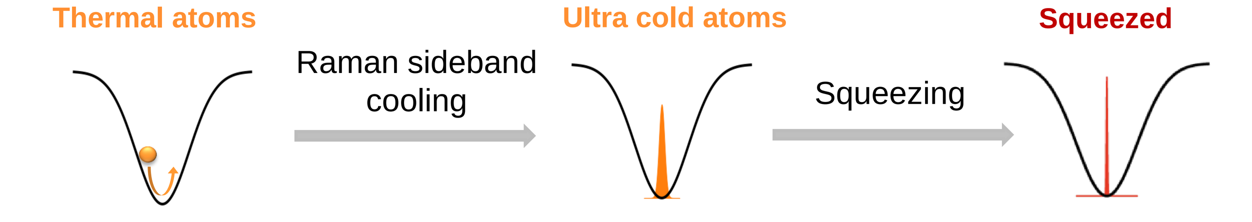


$J = \frac{C_3}{R^3}$ Interaction noise $\frac{\Delta J}{J} = 3\frac{\Delta R}{R}$ Position noise

- Ultrafast gates on Rubidium Rydberg atoms[1] (6.5 ns)
  - Strong dipole-dipole interaction $C_3 \approx 1\ \mathrm{GHz} \cdot \mu\mathrm{m}^3$
  - Direct interaction gate (ns)
  - **Requires control of inter atomic distance**



Ultrafast Föster oscillation[5]

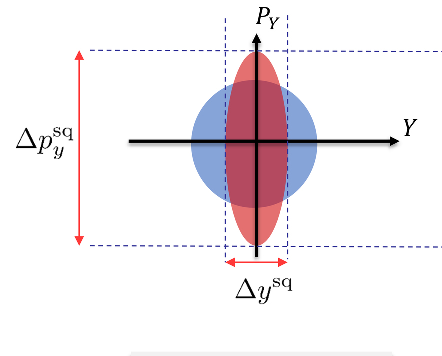


$\Delta y^{th} = \sqrt{\frac{k_B T}{m\omega^2}} \simeq 100\,\mathrm{nm}$, $T = 50\mu\mathrm{K}$

$\Delta y^{qu} = \sqrt{\frac{\hbar}{2m\omega}} = 25\,\mathrm{nm}$, $|\psi\rangle = |0\rangle$

$\Delta y^{sq} = \Delta y^{qu}/S$, $\Delta p_y^{sq} = \Delta p_y^{qu} \times S$

- **Squeezing to overcome Heisenberg uncertainty and increase 2-qubits gate fidelity (~ 2%)**
  - Already used by ion-trapped platforms, metrology, gravitational waves, in optical lattice[6] ….
  - **Squeezed states for optical tweezer ?**
  - **Squeezing factor goal : $S = 2 \rightarrow 6$ dB**



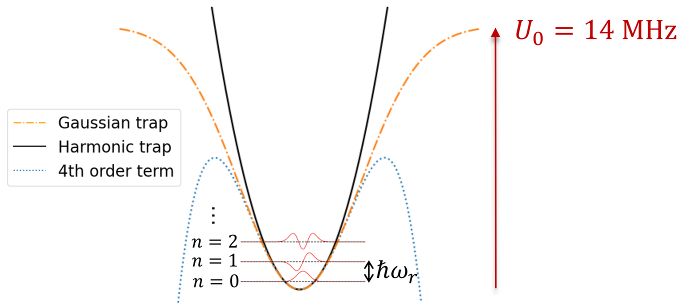
References

1. S. de Léséleuc et al. Observation of a symmetry-protected topological phase of interacting bosons with Rydberg atoms. Science 365,775 (2019).
2. H. Bernien et al. Probing many-body dynamics on a 51-atom quantum simulator. Nature 551, 579 (2017).
3. S. J. Evered et al. High-fidelity parallel entangling gates on a neutral atom quantum computer. arXiv:2304.05420 (2023).
4. A. M. Kaufman et al., Cooling a Single Atom in an Optical Tweezer to Its Quantum Ground State, Phys. Rev 2, 041014 (2012)
5. Y. Chew, et al. Ultrafast energy exchange between two single Rydberg atoms on a nanosecond timescale. Nat. Photon. 16, 724 (2022).
6. M. Morinaga et al., Manipulation of Motional Quantum States of Neutral Atoms, Physical Review Letters (1999).
7. C. Tuchendler et al., Energy distribution and cooling of a single atom in an optical tweezer, Phys. Rev. A **78**, 033425 (2008).
8. D. Jaksch et al., Fast quantum gates for neutral atoms PRL **85**, 2208 (2000).

Motional Squeezed states generation

Optical tweezers description

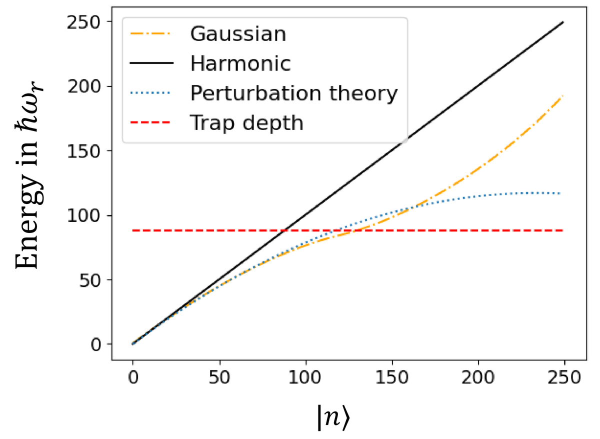
- The Gaussian potential can be approximated by a harmonic one
- We can ignore the z axis because $\omega_z \approx 30$kHz ($z_R \approx 1.7\ \mu m$). Moreover, Δz is a second order term in ΔR



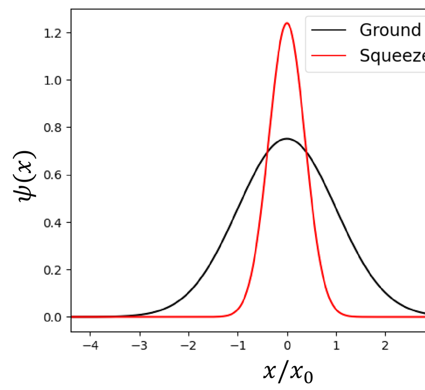
$$U(x) = -U_0 \exp(-2x^2/W_0^2) \approx -U_0 + \frac{1}{2}m\omega_r^2 x^2 - \frac{1}{2}m\omega_r^2 \epsilon \frac{x^2}{x_0^2}$$

with $\omega_r = \sqrt{\frac{4U_0}{mW_0^2}} \sim 120$ kHz ($W_0 \sim 0.6\mu m$),

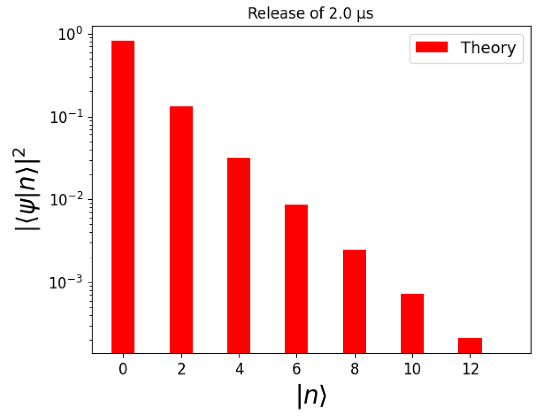
$\epsilon = \frac{\omega_r \hbar}{8U_0} \sim 2.10^{-3}$ and $x_0 = \sqrt{\frac{\hbar}{2m\omega_r}} \sim 20$nm



Gaussian trap and its approximations energy levels



Calculated squeezed state wavefunction ($\Delta x = \Delta x_0/2$)

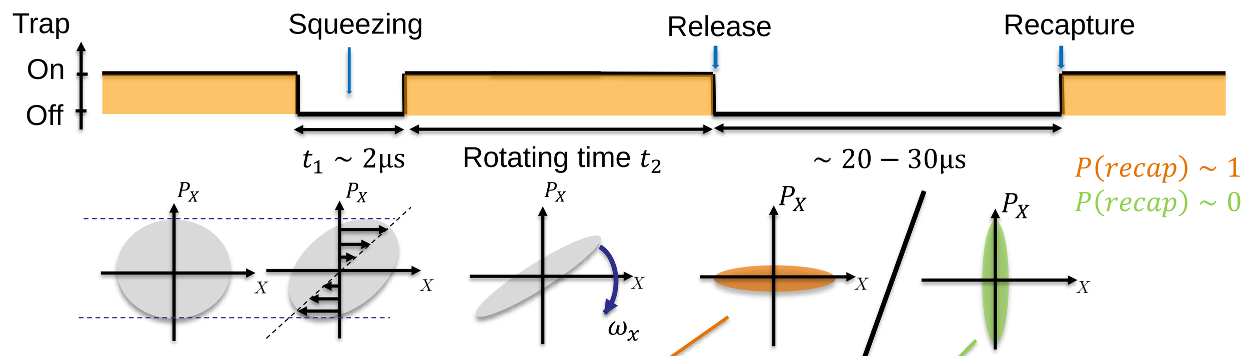


Calculated squeezed state distribution over Hamiltonian eigenstates ($\Delta x = \Delta x_0/2$)

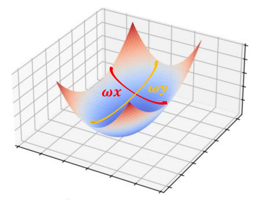
- Probability to have $n < 10$ is greater than 0.99 with Δx divided by a factor of 2
- The harmonic approximation is valid for squeezed states
- Atoms should remain in the trap as high levels are not populated

Generate motional squeeze states

- Turning off and on the trap squeeze the motional state

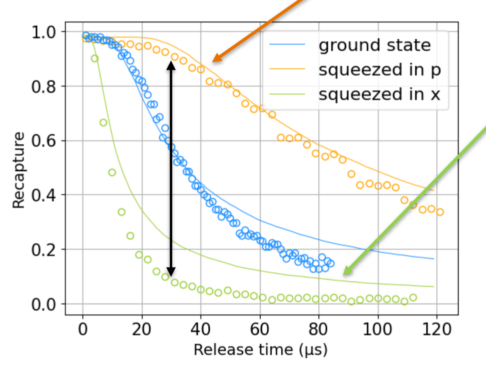


- In the phase space representation (Wigner distribution) upper points have more momentum. Therefore, they go further
- Squeezed states then rotate at trap frequency and are alternatively squeezed in position and momentum

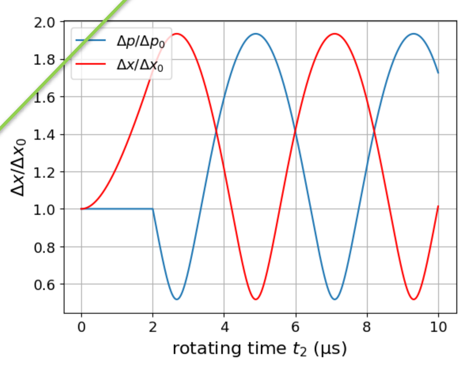


Anisotropic trap

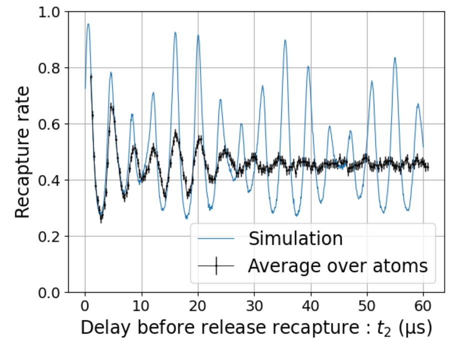
- Tweezer beam linear polarization along x axis induces asymmetry
- Squeezed states in the x-direction and y-direction do not oscillate at the same frequencies
- Global spread in r or p shows beatings



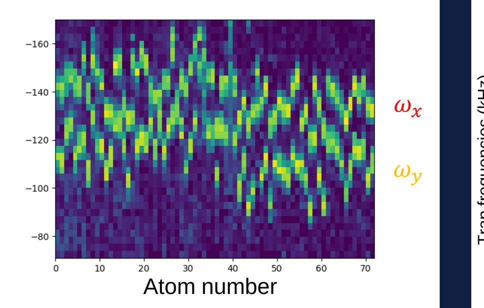
Recapture rate for different states after release for a variable time



Theoretical spread in x and p in one given direction



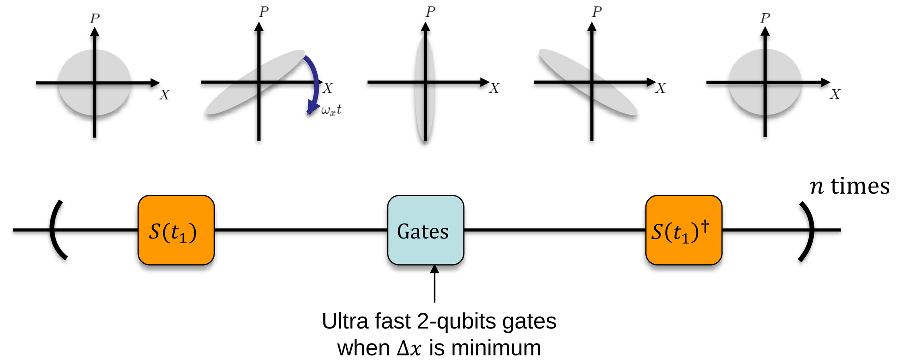
For different rotating times t_2 the atoms are released and recaptured



Trap frequencies for each different atom

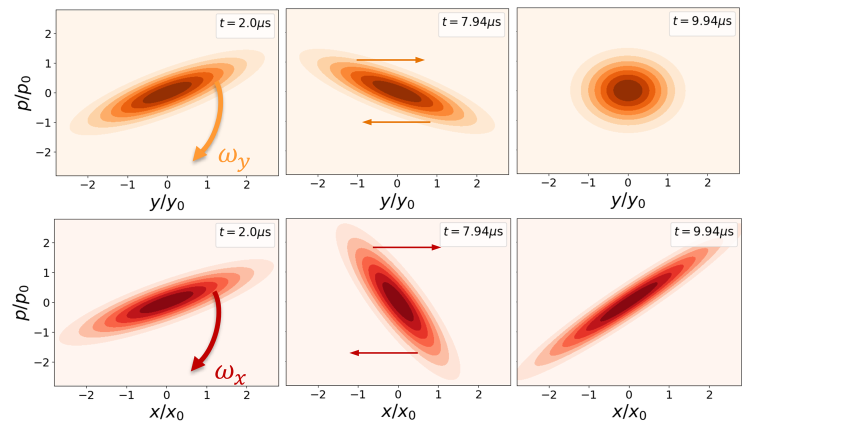
Squeezing fidelity

- To recover the ground state, the tweezer must be turned off when the squeezed state is in the position symmetric to the one after squeezing

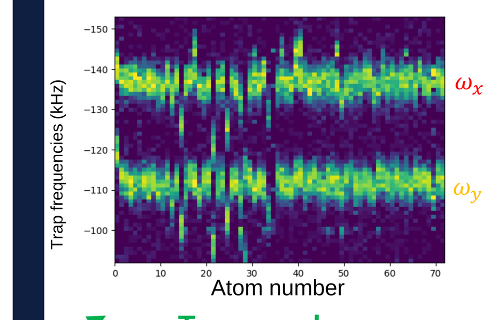


Traps Anisotropy and inhomogeneity

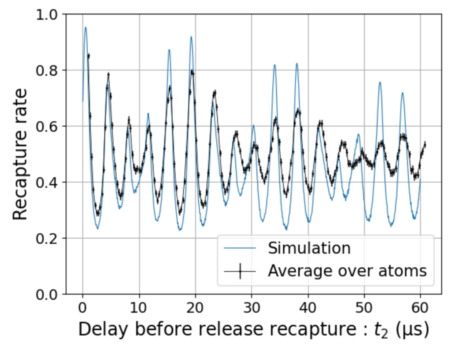
- Squeezed states from different atoms and axis evolve at different frequencies
- They cannot be unsqueezed all together
- Trap frequencies are homogenized and equalized by optimizing the SLM phase pattern

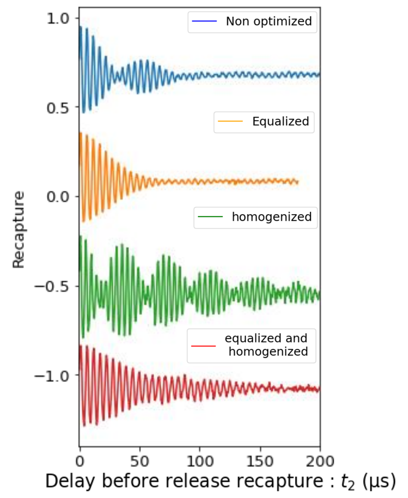


- Atoms minimum position spreads are then reached at the same time (along a given axis)



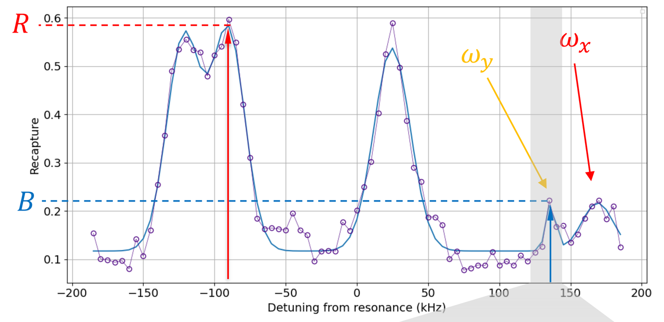
Tweezer shape homogenization

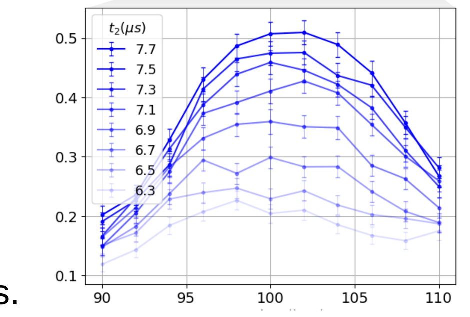




- Multiple squeeze unsqueeze for multiple 2-qubits gates
- A high squeezing-unsqueezing fidelity is required to allow for a good 2-qubits gate fidelity
- Fidelity is measured with Raman spectroscopy. Adiabatic transition amplitudes give access to $\Delta n = -1$ and $\Delta n = +1$ transitions probabilities :

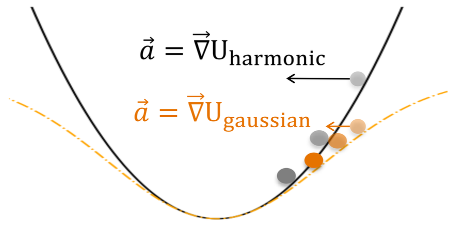
$F_y = |\langle\psi_y|0\rangle|^2 = 1 - \frac{B}{R}$

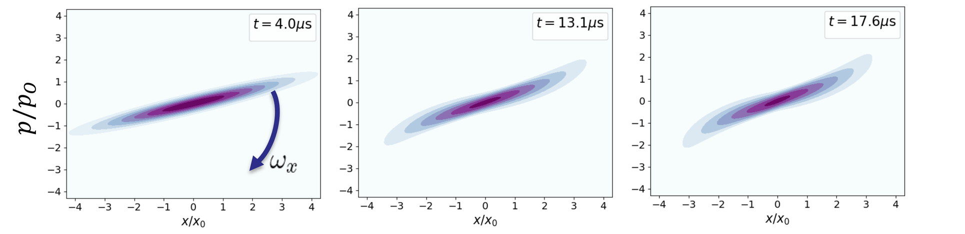




Traps anharmonicity

- Far from the tweezer center, the trap is anharmonic:
  - Higher eigenstates of the trap correspond to lower energies. Their phase evolve more slowly than in the harmonic case
  - In the phase space representation, points far from center rotate more slowly

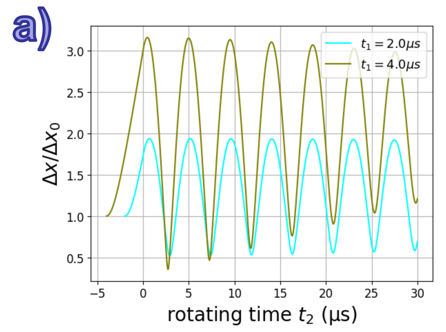




Wigner representation of a 4μs squeezed state in an anharmonic trap

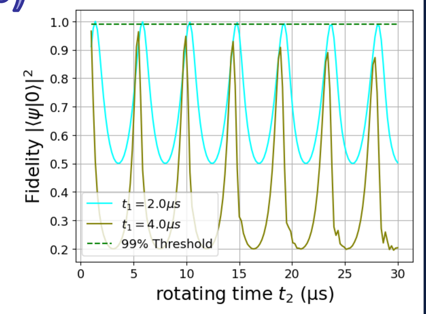
- The more a state is squeezed, the more it explores anharmonic parts of the trap and the more it gets deformed.
  - Squeezing quality decreases with time (see **a)**)
  - It makes it impossible to recover the ground state (see **b)**)

a)



Position spread for a 2μs and a 4μs squeezed state:

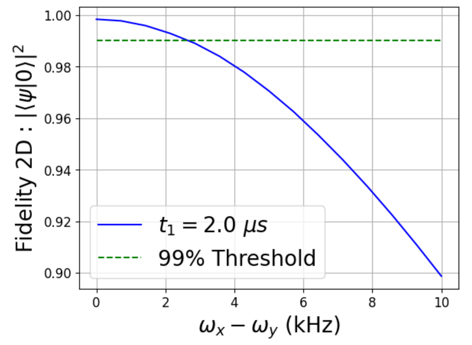
b)



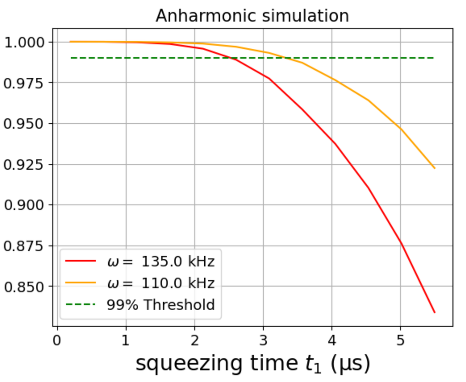
Ground state fidelity for a 2μs and a 4μs squeezed state:

Outlook

- Take SPAM errors into account for more accurate fidelity measurement
- Bring the ω_x and ω_y trap frequencies together with apodization technic to increase fidelities and compare with theory (below)



- Determine the experimental maximum squeezing factor that can be reached with 99% fidelity. Compare with theory (below)



- Study the influence of trap depth on anharmonicity
- **Measure ultrafast 2-qubits gates improvement with squeezed states**
- Quantum amplification to measure Rydberg attraction kick