# Ultrafast Rydberg experiments with ultracold atoms in optical tweezers


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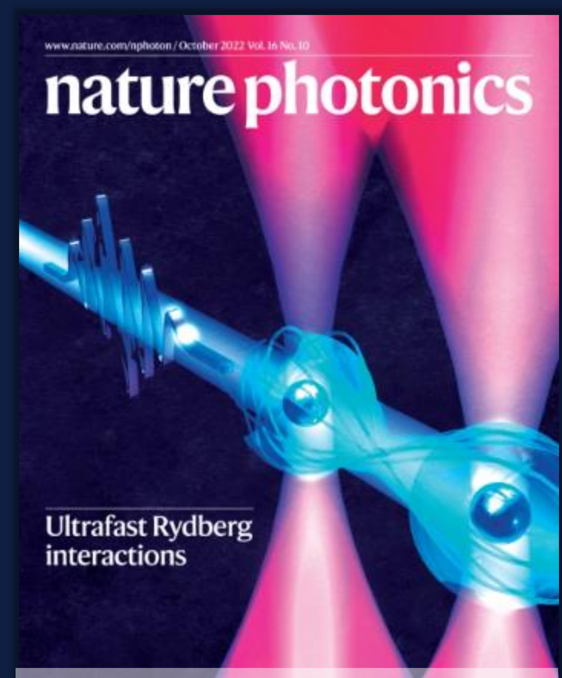
moonshot 大森 PM Goal 6 大規模・高コヒーレンスな動的原子アレー型・誤り耐性量子コンピュータ

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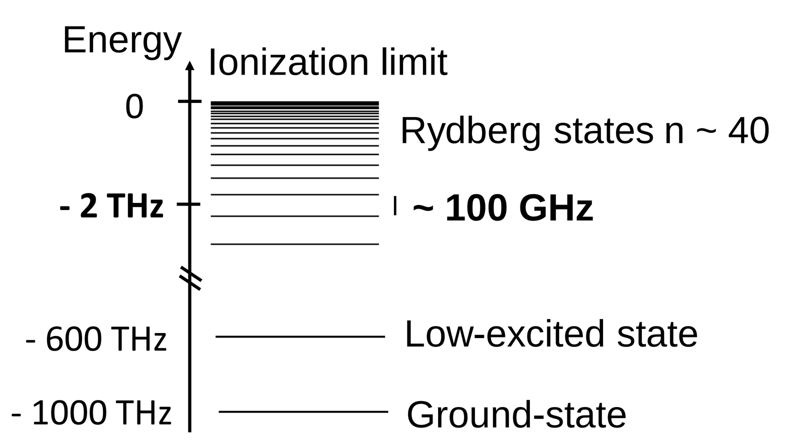
## Rydberg timescale

### Rydberg states

$$E_n = -\frac{13.6\,\mathrm{eV}}{n^2}$$




**Ultrafast** — **Fast** — **Slow**

Binding energy | Rydberg state splitting | *No investigations here so far…* | *95% of Rydberg experiments are here* | Rydberg lifetime

1 ps — 10 ps — 100 ps — 1 ns — 10 ns — 100 ns — 1 µs — 10 µs — 100 µs — 1 ms

Ultrafast excitation $\Omega_{\mathrm{pulsed}} \gg J$ Ultrafast interaction | Rydberg blockade $V \gg \Omega_{\mathrm{cw}}$ cw excitation | *a few groups are working here (Rydberg dressing, circular states)*

ARTICLES — nature photonics

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OPEN

**Ultrafast energy exchange between two single Rydberg atoms on a nanosecond timescale**

Y. Chew[1,2], T. Tomita[1], T. P. Mahesh[1], S. Sugawa[1,2], S. de Léséleuc[1,2] and K. Ohmori[1,2]

- ✓ Entered the ultrafast regime
- ✓ Controlled excitation in 10 ps
- ✓ Controlled interaction in <10 ns

### Dipole-dipole interaction

$$\hat{H}_{\mathrm{dip}} \sim \frac{\hat{d}_1 \hat{d}_2}{4\pi\epsilon_0 R^3}$$

$$J = \frac{C_3}{R^3} \gg V = \frac{C_6}{R^6}$$

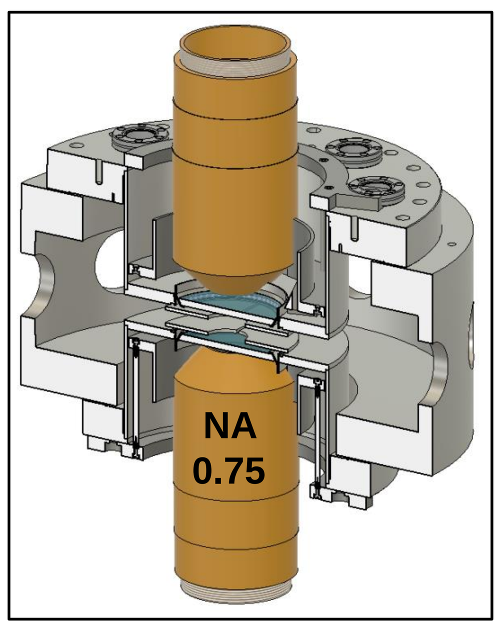
First-order (resonant dip-dip) — Second-order (van der Waals)

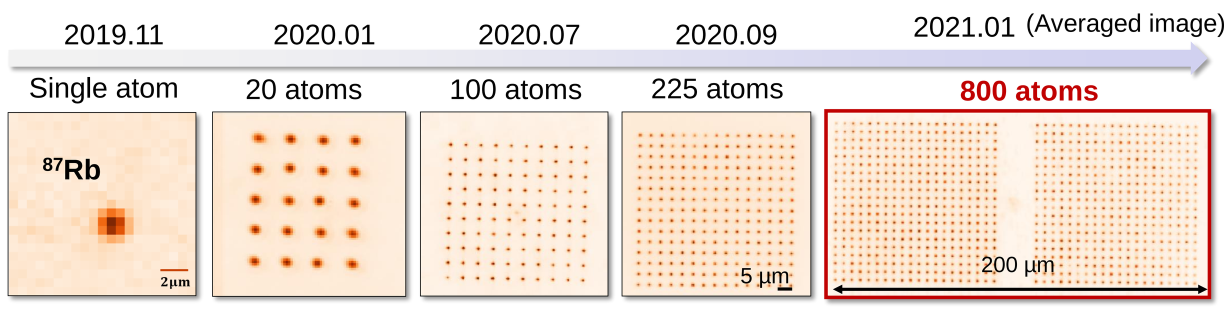
$$C_3 \sim 1\,\mathrm{GHz}.\mu\mathrm{m}^3$$

1 µm -> **nanosecond timescale !**

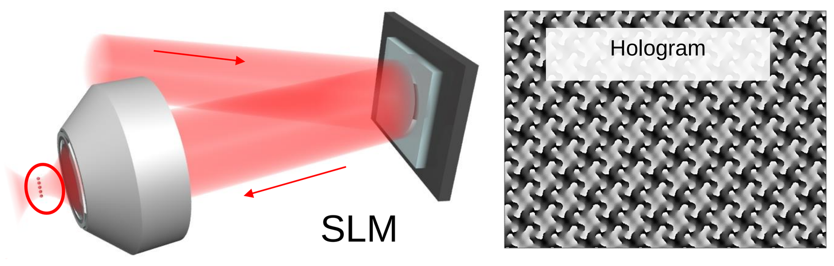
## Ultracold atoms in tweezers

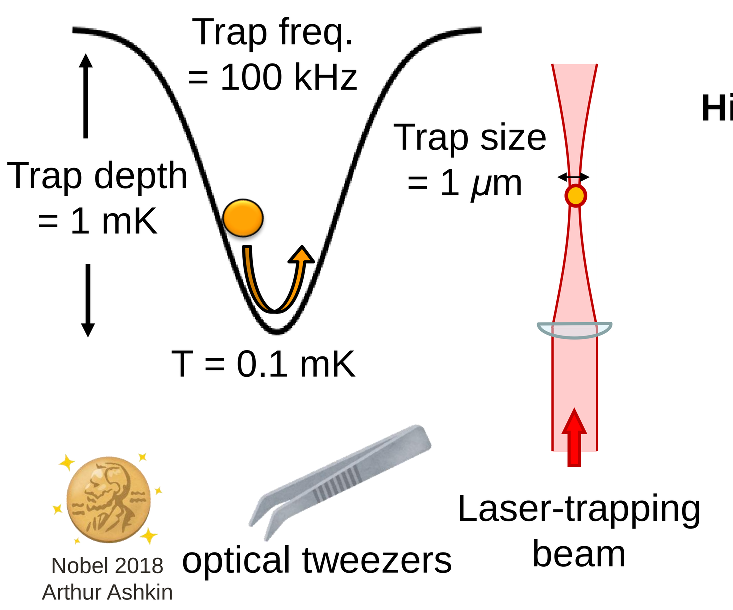
### Arrays of holographic optical tweezers



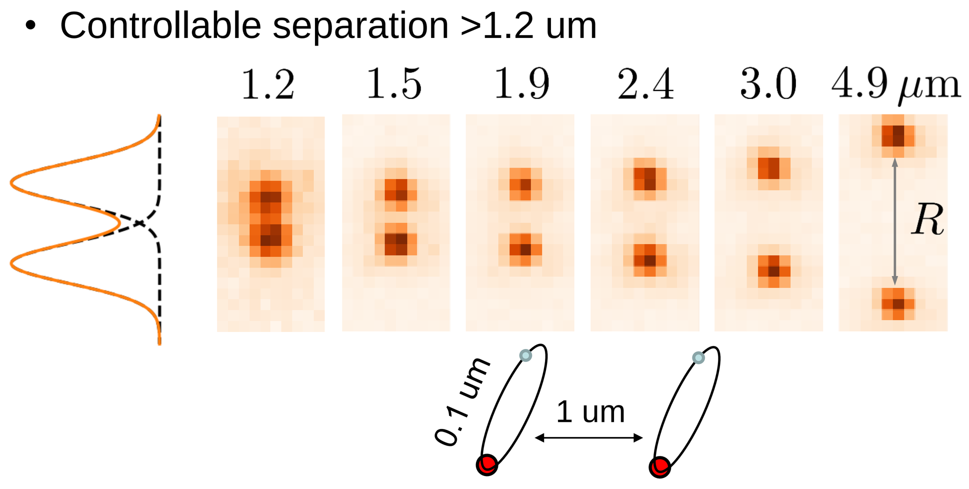

Single cold-atom in tweezers




**High NA: Small tweezers**

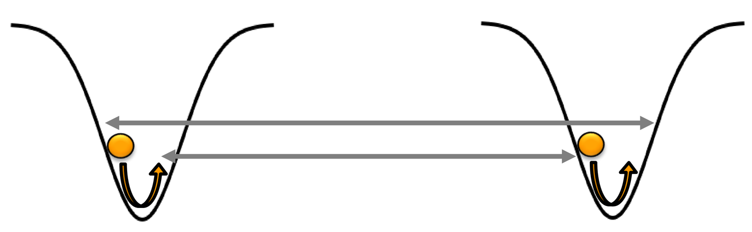
- Waist: 600 nm
- Controllable separation >1.2 um



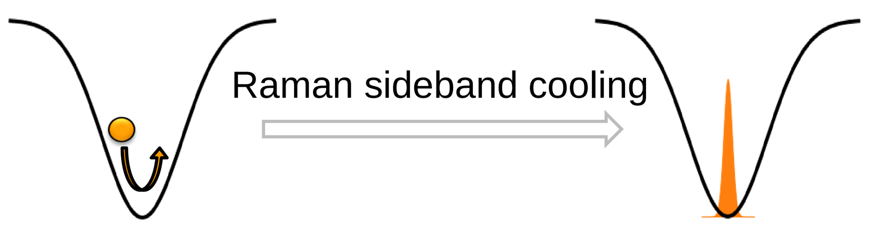

### Quantum-limited control of position

**Uncertainty of distance is a problem …**

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

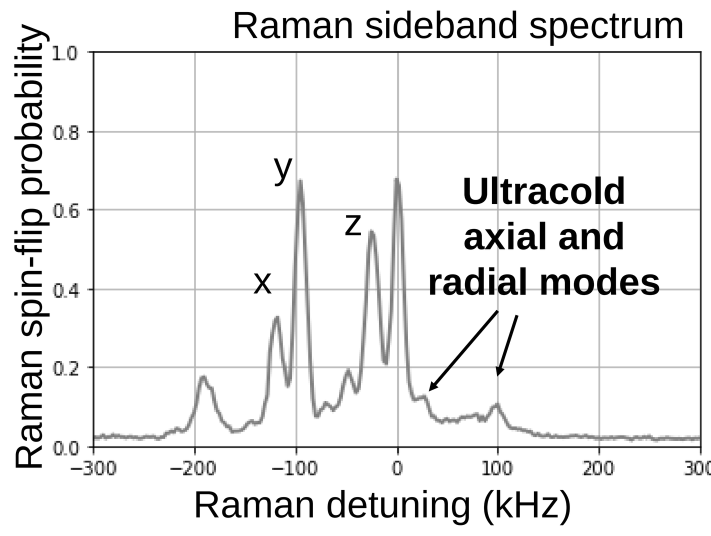


**… improved down to the quantum limit**



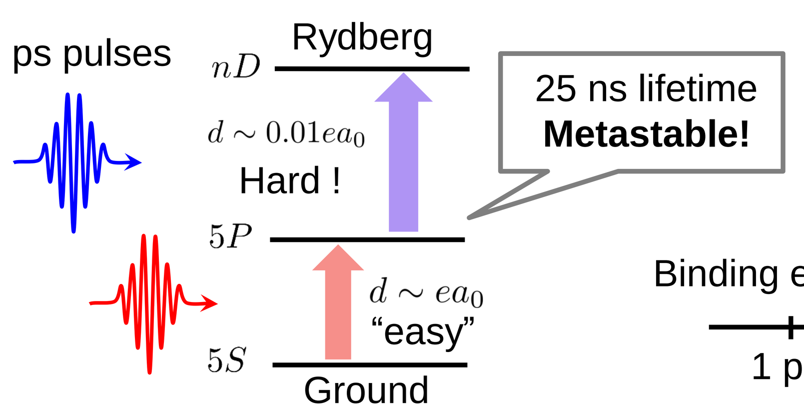

Thermal fluctuations — Quantum fluctuations

$$\Delta y = \sqrt{\frac{k_B T}{m\omega^2}} \simeq 100\,\mathrm{nm} \qquad \Delta y = \sqrt{\frac{\hbar}{2m\omega}} = 25\,\mathrm{nm}$$

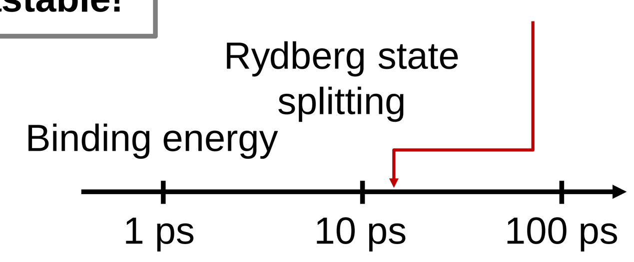



## Ultrafast Rydberg

### Ultrafast Rydberg excitation (picosecond)

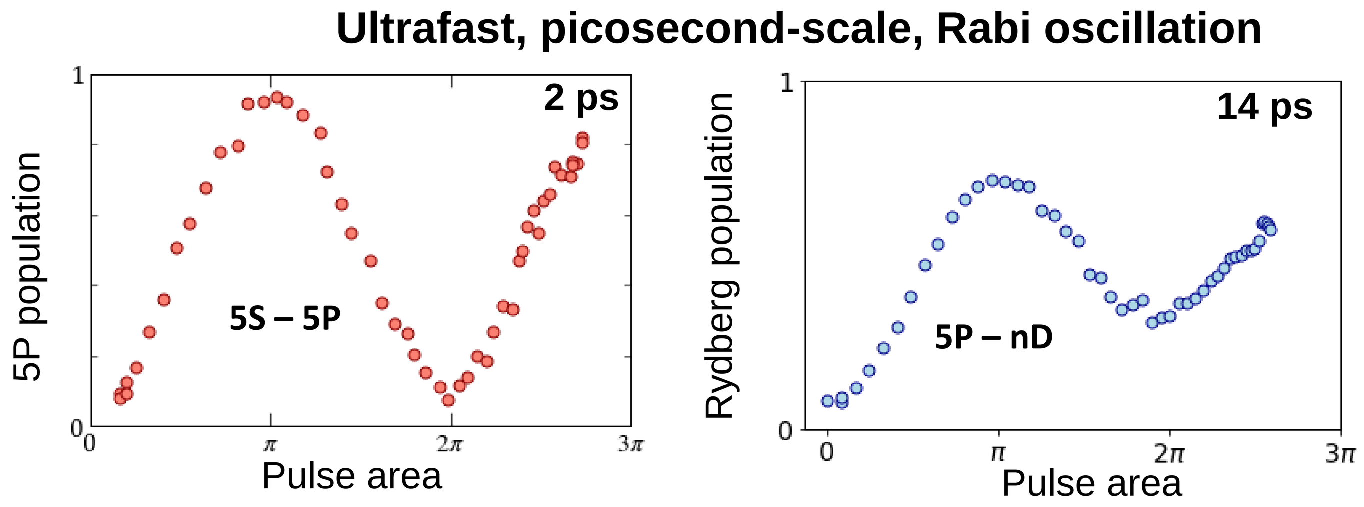



As **FAST** as possible !




Speed:
- Limited by physics
- **Not** limited by tech.

**Ultrafast, picosecond-scale, Rabi oscillation**

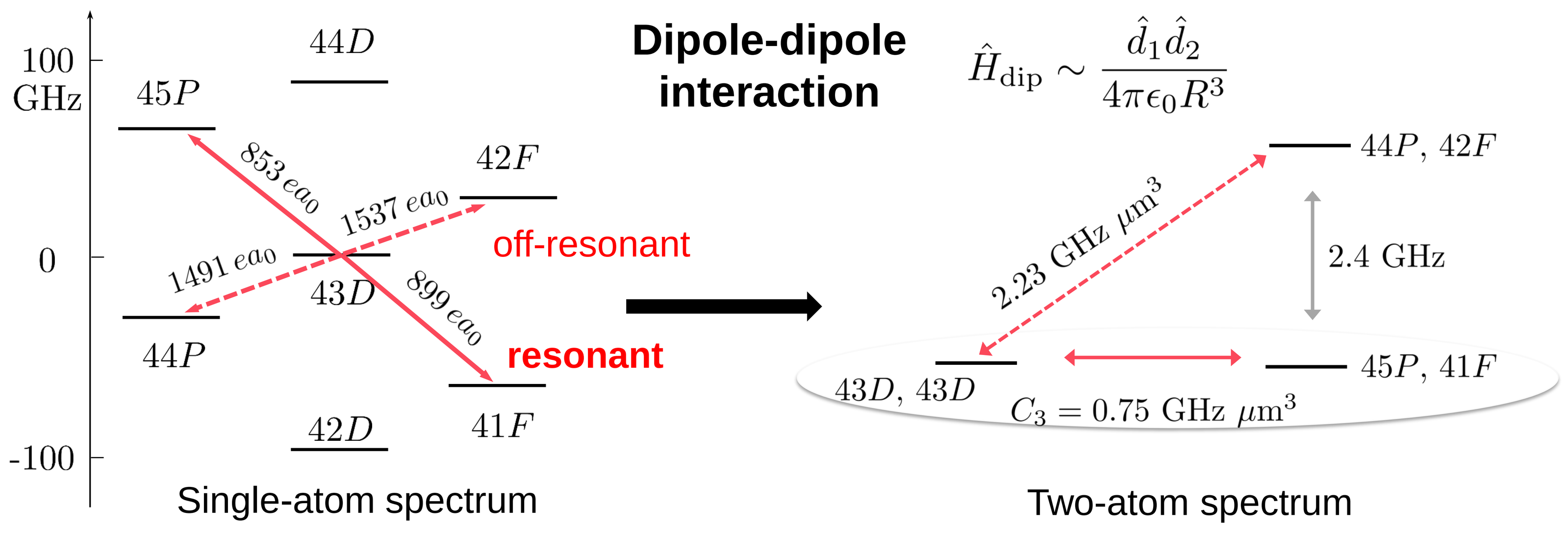



Damping: Pulse-to-pulse energy fluctuation

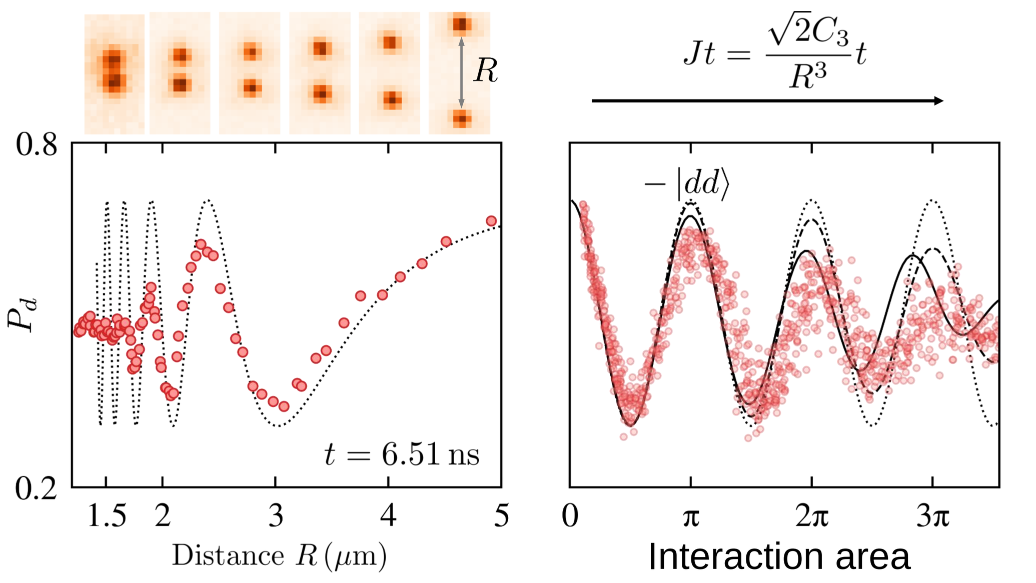
### Ultrafast Rydberg interaction (nanosecond)

**Dipole-dipole interaction**

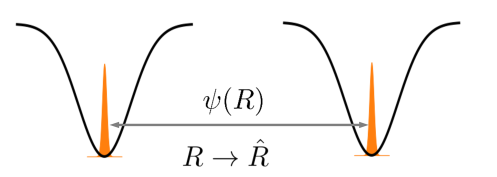
$$\hat{H}_{\mathrm{dip}} \sim \frac{\hat{d}_1 \hat{d}_2}{4\pi\epsilon_0 R^3}$$




**Ultrafast, nanosecond-scale, Förster oscillation**




**Theory**
- ➢ Dotted: ab-initio $C_3$
- ➢ Dashed: entanglement with motion



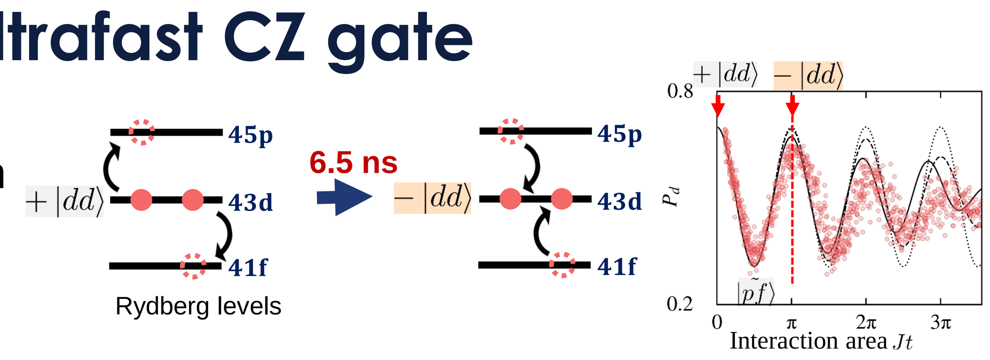

$$\Psi(t) = \int dR\,\psi(R)\left[\cos\left(\frac{\sqrt{2}C_3}{R^3}t\right)|R;dd\rangle - i\sin\left(\frac{\sqrt{2}C_3}{R^3}t\right)|R;\tilde{pf}\rangle\right]$$

- ➢ Solid: off-resonant channels

## Outlooks

### Interaction-driven ultrafast CZ gate

- Use an orbital resonance between atoms to quickly imprint a conditional $\pi$-phase shift



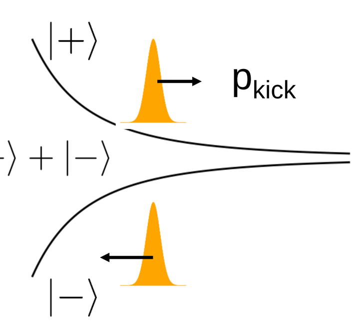

- Advantage: resilient to noise (E-field, finite lifetime, scattering, Doppler, …)
- Challenge: need to control interaction (many interaction channels, coupling to motion…)

### Entanglement to motion

- Mechanical force on the atoms: let's measure the momentum kick !
- Use squeezed state of motion to amplify or suppress the kick
- The kick entangles the motion of the two atoms: let's explore this !

❑ Wavefunction representation

$$|dd\rangle = |+\rangle + |-\rangle$$




**Momentum kick**

$$p_{\mathrm{kick}} = 3Jt\frac{\hbar}{R} \simeq \Delta p_{\mathrm{qu}}$$

❑ Phase-space representation