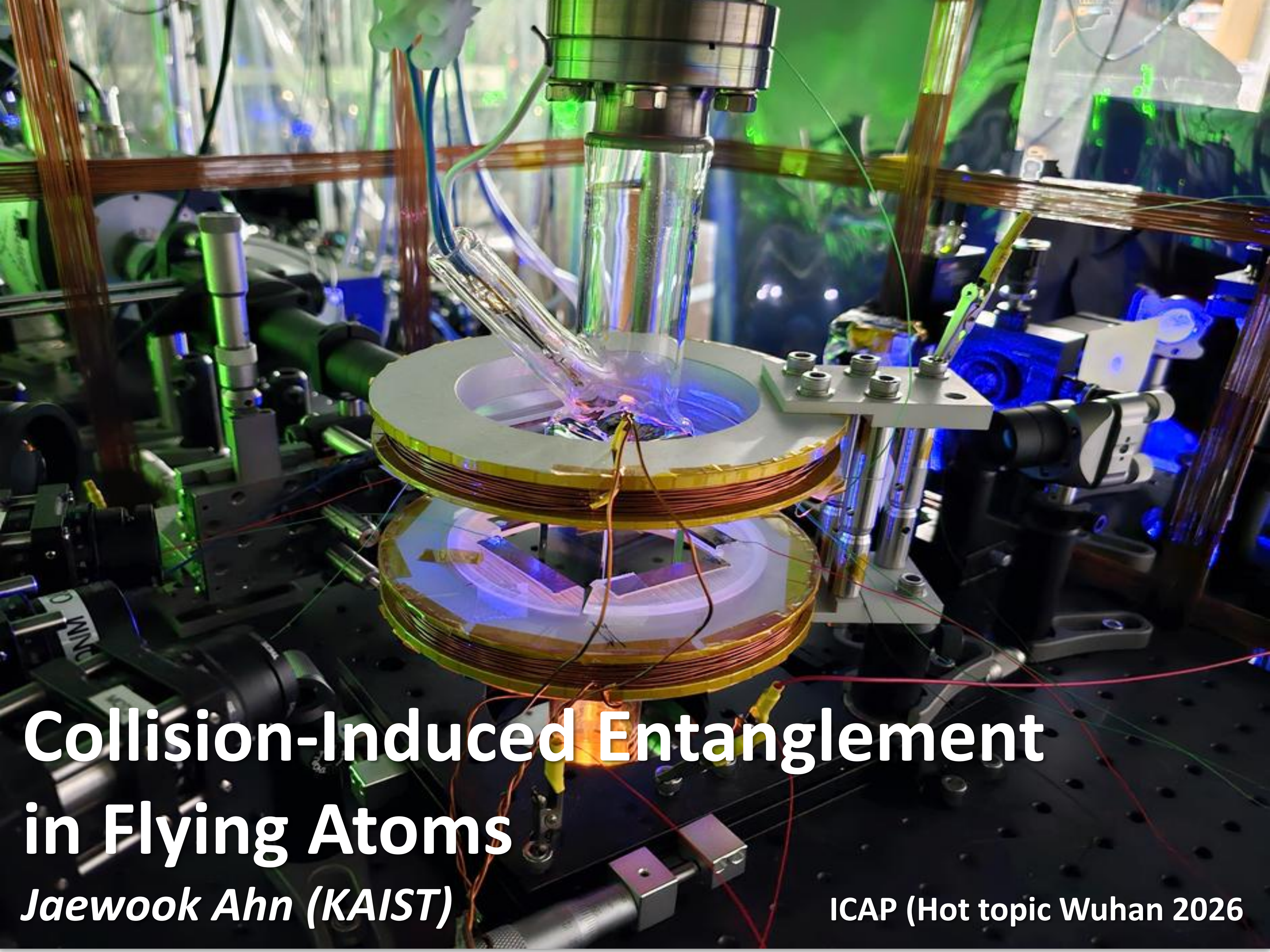
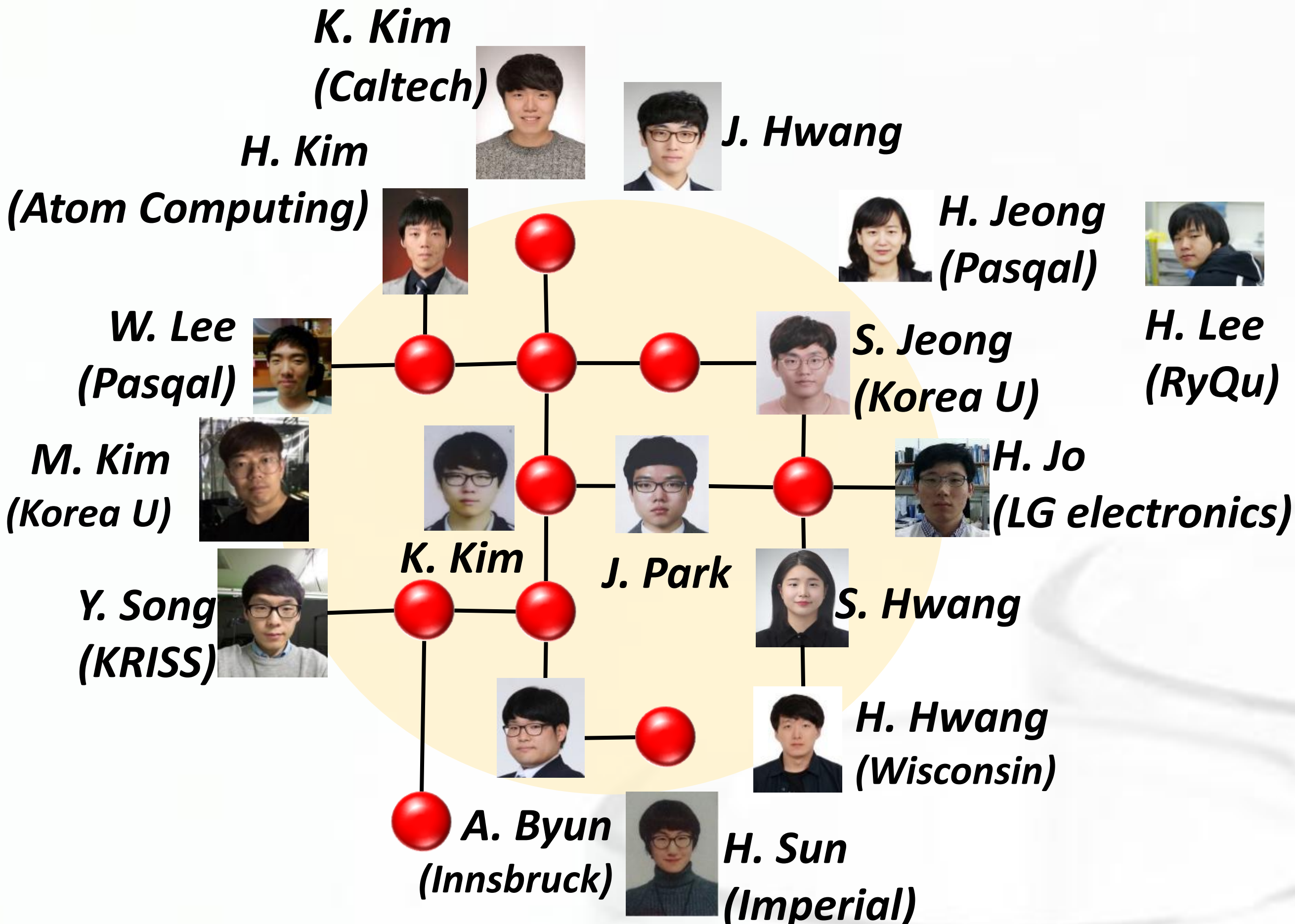


Collision-Induced Entanglement in Flying Atoms

Jaewook Ahn (KAIST)

ICAP (Hot topic Wuhan 2026

Rydberg Quantum Computing Team at KAIST



Funded by

Collision-Induced Entanglement of two flying atoms

Rydberg-ground superposition

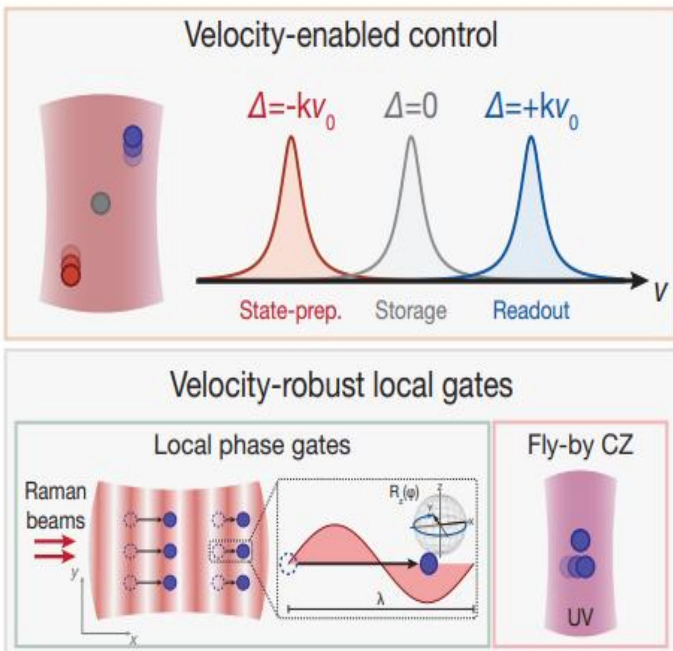
Atom-atom interaction ≈ Frozen gas approximation
* Atoms remain stationary

→ Coherence

Motional effec
- Interaction-
- Spin-motio
- Motion → C

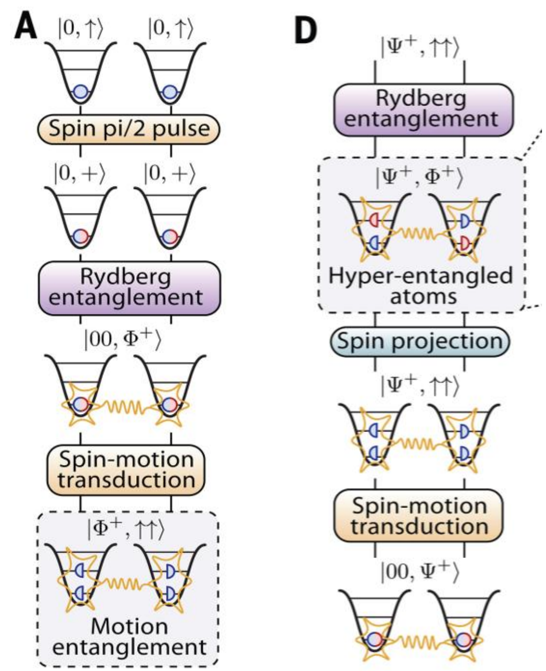
Progress in c
- Coherent c
- Actively co

Velocity-Enabled Quantum Computing



O. Lib et al, 2026, arXiv:2603.15561

Erasure cooling and control



A. L. Shaw et al, 2025, Science

Collision-Induced Entanglement of two flying atoms

Rydberg-ground superposition

Atom-atom interaction ≈ Frozen gas approximation
* Atoms remain stationary
* Time-independent interactions
* Qubit dynamics dominant

→ Coherence, correlations, entanglements w/o atomic motions

Motional effects in interacting Rydberg systems

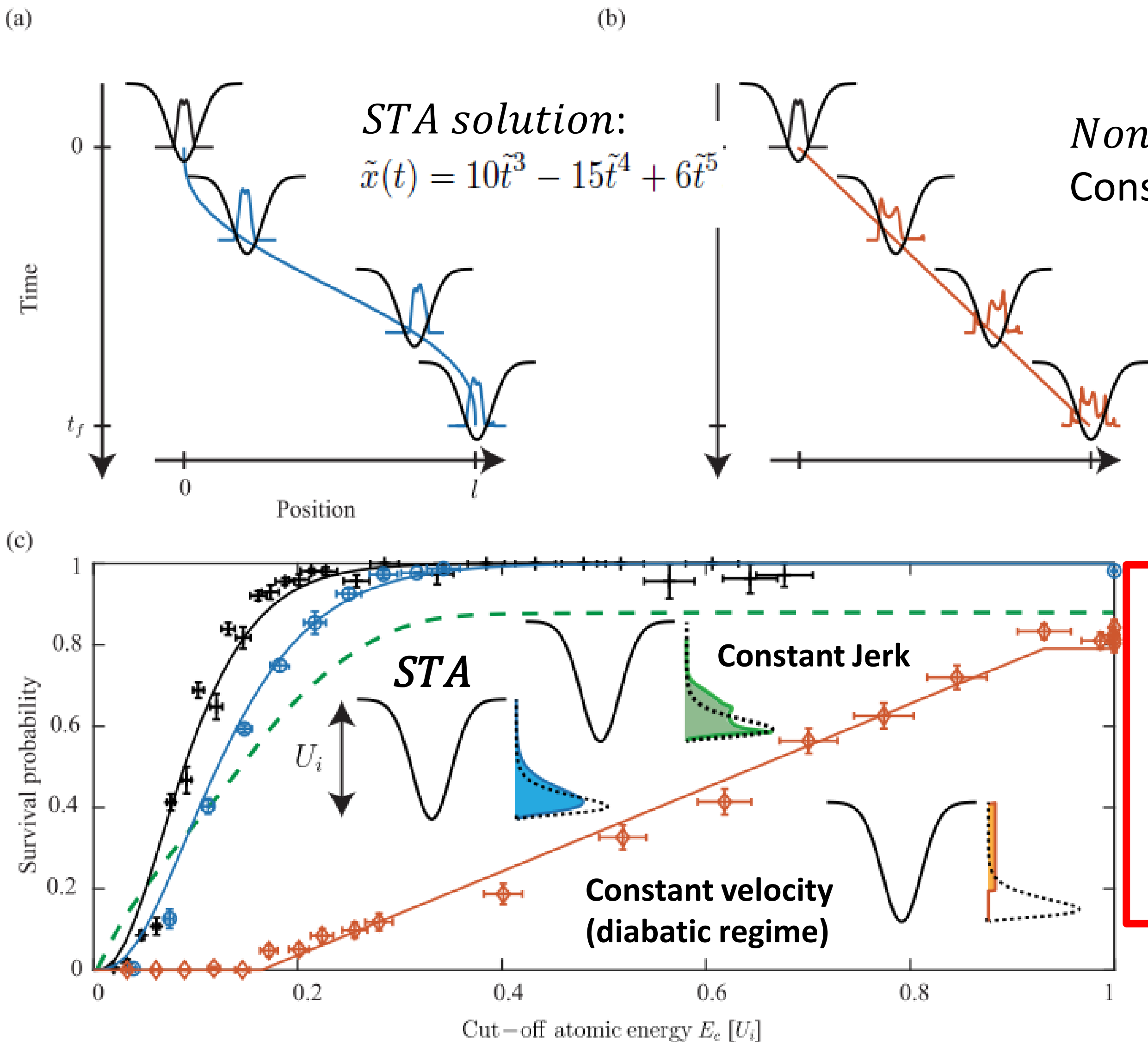
- Interaction-induced spectral broadening [Lesanowsky,Pfau]
- Spin-motion correlations, state-dependent dynamics [Broways, Omori]
- Motion → Gate infidelity [Saffman]

Progress in control of trapping potentials and cooling technique

- Coherent control of single atoms in motion (atom throw and catch)
- Actively controllable motional degree of freedom (internal + motional)

→ Motion may become controllable quantum resource

Shortcut-to-Adiabaticity (STA) passage

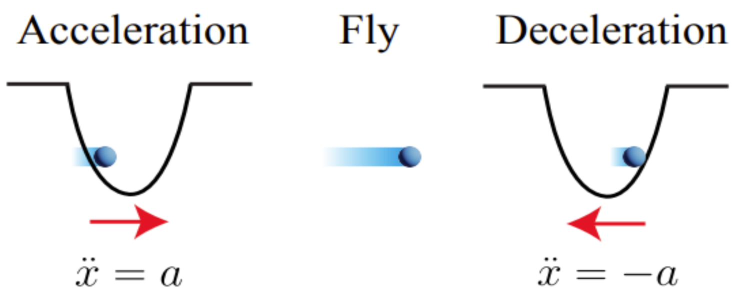


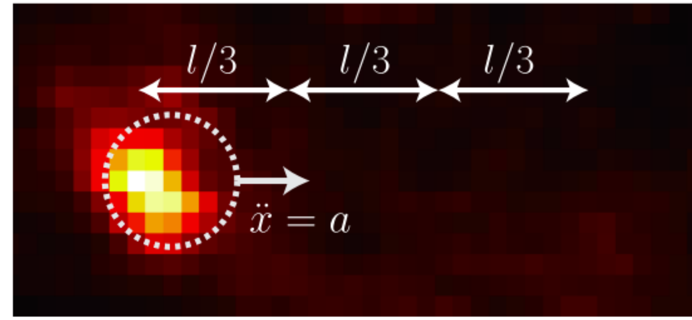
Non-STA solution:
Constant velocity at diabatic regime

$$l_{\max} = \begin{cases} \sqrt{\dfrac{2U_0}{m}} \times t_f & \text{for CV path,} \\ \dfrac{1}{3\sqrt{3}} \dfrac{U_0}{md} \times t_f^2 & \text{for CJ path,} \\ \dfrac{\sqrt{3}}{5} \dfrac{U_0}{md} \times t_f^2 & \text{for STA path.} \end{cases}$$

Sunhwa Hwang et al., "Fast and reliable atom transport by optical tweezers," Optica Quantum 3, 64 (2025).

Atom throw-and-catch by optical tweezers



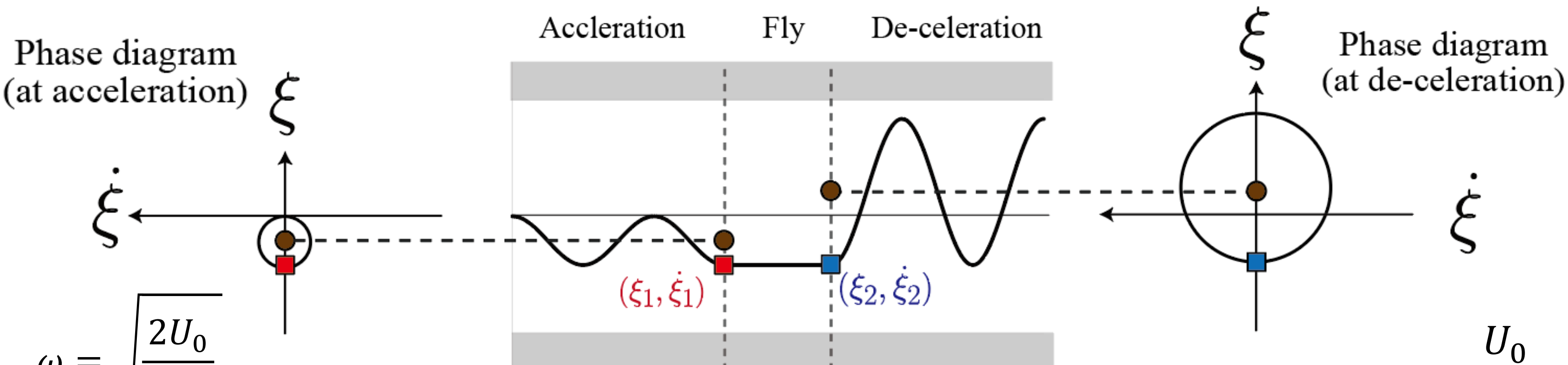


Optical tweezer
= a truncated harmonic potential

$$U(\xi) = \frac{U_0}{d^2}(\xi - d)(d + \xi)$$

Relative atom position from trap center

$$\xi(t) = -\frac{\ddot{x}}{\omega^2} + A\cos(\omega t + \phi)$$



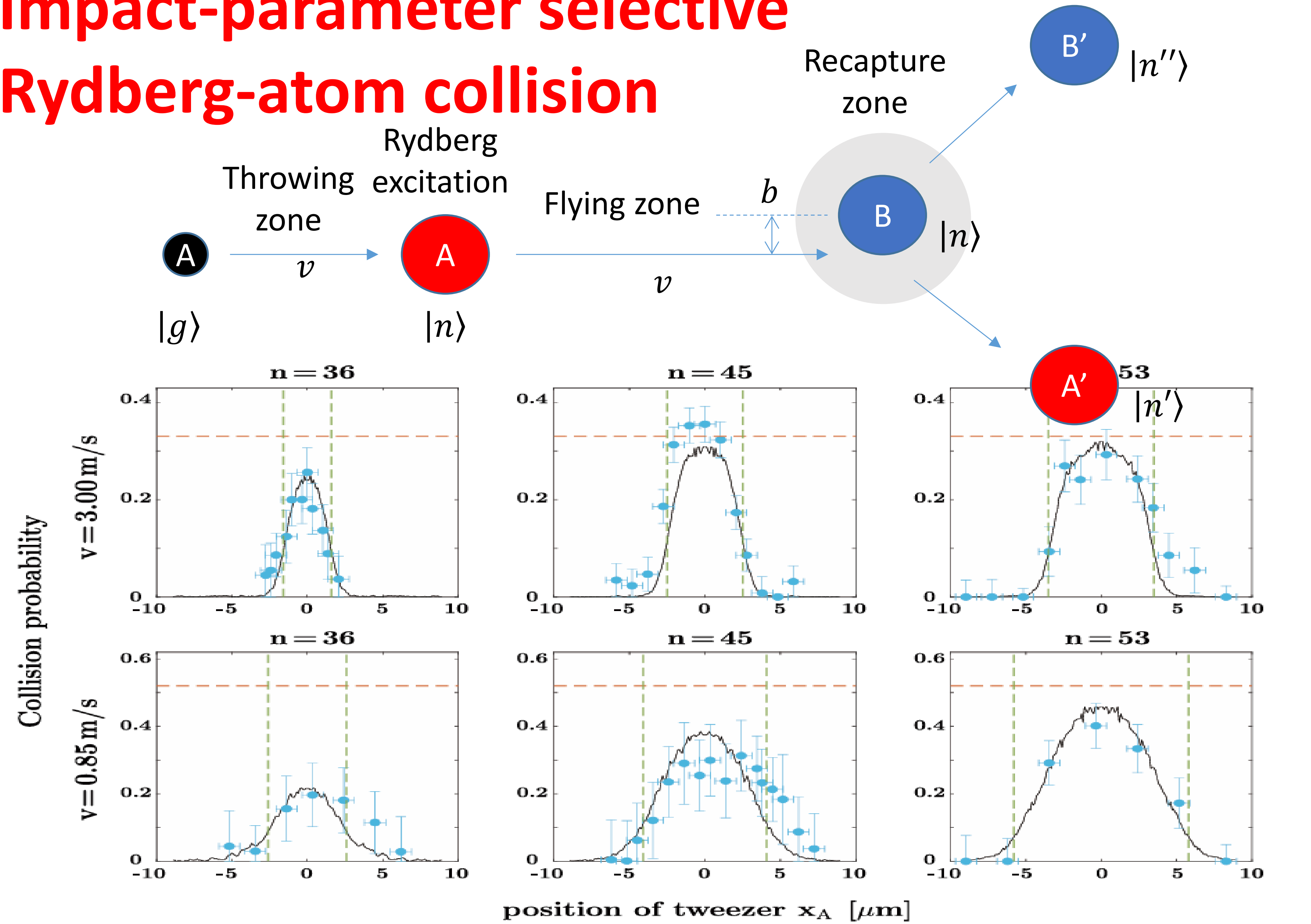
$$\omega = \sqrt{\frac{2U_0}{md^2}}$$

$$a_{max} \approx \frac{U_0}{md}$$

Experiment Time

H. Hwang et al., "Optical tweezers throw and catch single atoms," Optica 10, 401 (2023).

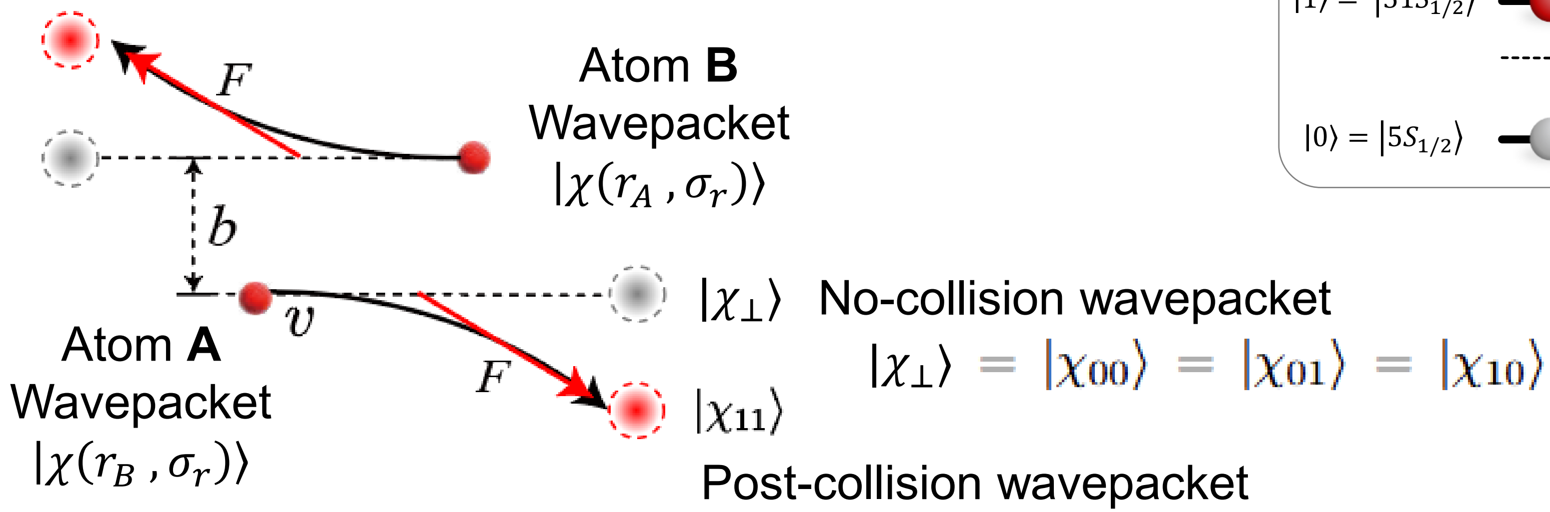
Impact-parameter selective Rydberg-atom collision

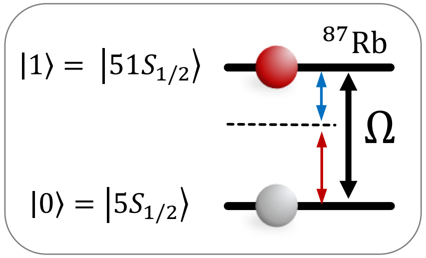


H. Hwang et al., "Impact-parameter selective Rydberg atom collision …," JPB 58, 115202 (2025)

Atom “Soft” Collision Scenario

Counter-moving atom pair (A,B)





$$\mathcal{H}_{\mathrm{tot}} = \mathcal{H}^{\mathrm{int}} \otimes \mathcal{H}^{\mathrm{mot}} = \left[\mathcal{H}_A^{\mathrm{int}} \otimes \mathcal{H}_B^{\mathrm{int}}\right] \otimes \mathcal{H}^{\mathrm{mot}}$$

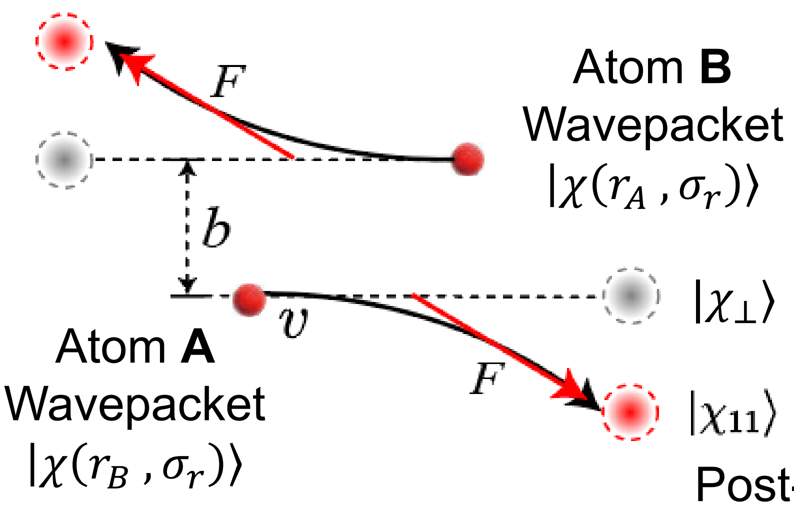
$$|\Psi\rangle = \sum_{ij} c_{ij}\, |ij\rangle \otimes |\chi_0\rangle$$

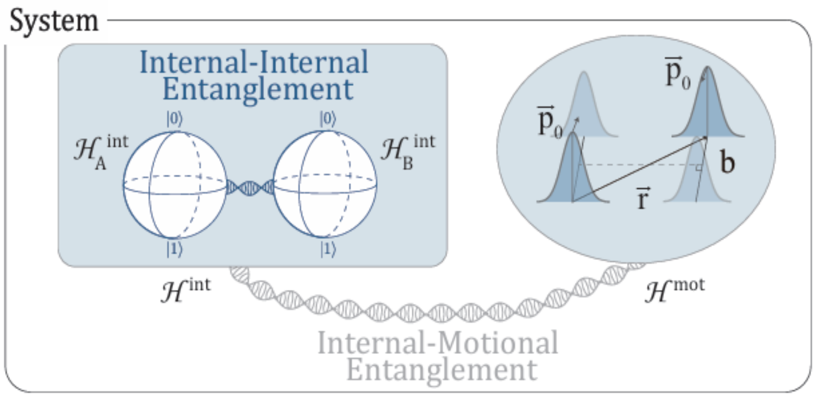
$$|\Psi\rangle = \sum_{\alpha \neq 11} c_\alpha |\alpha\rangle \otimes |\chi_A\rangle + c_{11}\, |11\rangle \otimes |\chi_{11}\rangle$$

$V(\hat{r})|11\rangle\langle 11|$: *Interaction only on* $|11\rangle$

Atom "Soft" Collision Scenario

Counter-moving atom pair (A,B)





No-collision wavepacket

$$|\chi_\perp\rangle = |\chi_{00}\rangle = |\chi_{01}\rangle = |\chi_{10}\rangle$$

Post-collision wavepacket

$$\mathcal{H}_{\text{tot}} = \mathcal{H}^{\text{int}} \otimes \mathcal{H}^{\text{mot}} = \left[\mathcal{H}_A^{\text{int}} \otimes \mathcal{H}_B^{\text{int}}\right] \otimes \mathcal{H}^{\text{mot}}$$

$$|\Psi\rangle = \sum_{ij} c_{ij}\, |ij\rangle \otimes |\chi_0\rangle \qquad |\Psi\rangle = \sum_{\alpha\neq 11} c_\alpha |\alpha\rangle \otimes |\chi_A\rangle + c_{11}\, |11\rangle \otimes |\chi_{11}\rangle$$

$V(\hat{r})|11\rangle\langle 11|$: *Interaction only on* $|11\rangle$

Different internal states → different motion

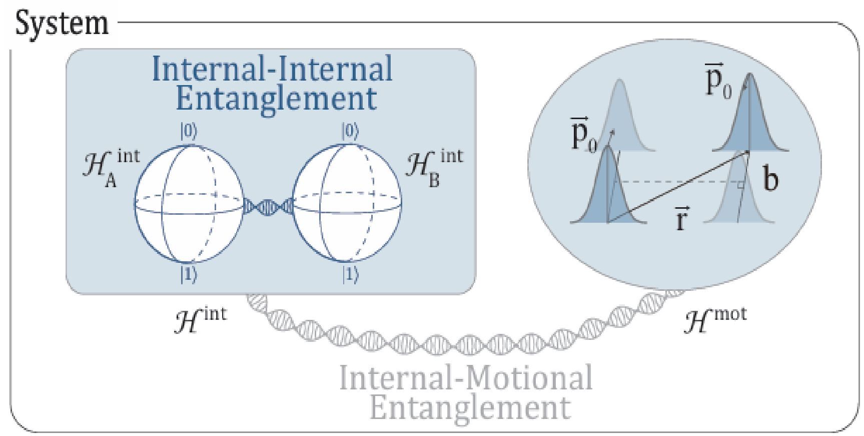
Collision Model

$$H = H_{\rm int} + H_{\rm drive} + H_{\rm col}$$

$$H_{\rm int} = -\frac{\hbar\Delta}{2}\sum_{i=A,B}\sigma_z^{(i)}$$

$$H_{\rm drive} = \frac{\hbar\Omega(t)}{2}\sum_{i=A,B}\left(e^{i\phi}\sigma_+^{(i)} + e^{-i\phi}\sigma_-^{(i)}\right)$$

$$H_{\rm col} = \frac{\hat{p}^2}{2\mu} + V_{\rm vdW}(\hat{r})|11\rangle\langle 11|$$



$$|\Psi\rangle = \sum_{ij} c_{ij}\,|ij\rangle \otimes |\chi_0\rangle$$

Initial motional wavepacket

$$U_{\rm int}(t) = \mathcal{T}\exp\left(-\frac{i}{\hbar}\int_0^t H_{\rm col}(t')dt'\right)$$

$$|\Psi(t)\rangle = \sum_{ij} c_{ij}\,|ij\rangle \otimes |\chi_{ij}(t)\rangle$$

Conditional motional state $|11\rangle$ *state only*

Collision Model with motional overlap

$$H = H_{\text{int}} + H_{\text{drive}} + H_{\text{col}}$$

$$H_{\text{int}} = -\frac{\hbar\Delta}{2}\sum_{i=A,B}\sigma_z^{(i)}$$

$$H_{\text{drive}} = \frac{\hbar\Omega(t)}{2}\sum_{i=A,B}\left(e^{i\phi}\sigma_+^{(i)} + e^{-i\phi}\sigma_-^{(i)}\right)$$

$$H_{\text{col}} = \frac{\hat{p}^2}{2\mu} + V_{\text{vdW}}(\hat{r})|11\rangle\langle 11|$$

Motional overlap

$$\gamma = \langle\chi_\perp|\chi_{11}\rangle = \int d\mathbf{r}\,\gamma(\mathbf{r})$$

$$|\Psi(t)\rangle = \sum_{ij} c_{ij}\,|ij\rangle \otimes |\chi_{ij}(t)\rangle$$

Motional traced out

$$\rho_{\text{int}} = \text{Tr}_{\text{mot}}[\rho]$$

$$\rho_{\text{int}}^{(4)} = \frac{1}{4}\begin{pmatrix} 1 & 1 & 1 & \gamma^* \\ 1 & 1 & 1 & \gamma^* \\ 1 & 1 & 1 & \gamma^* \\ \gamma & \gamma & \gamma & 1 \end{pmatrix}$$

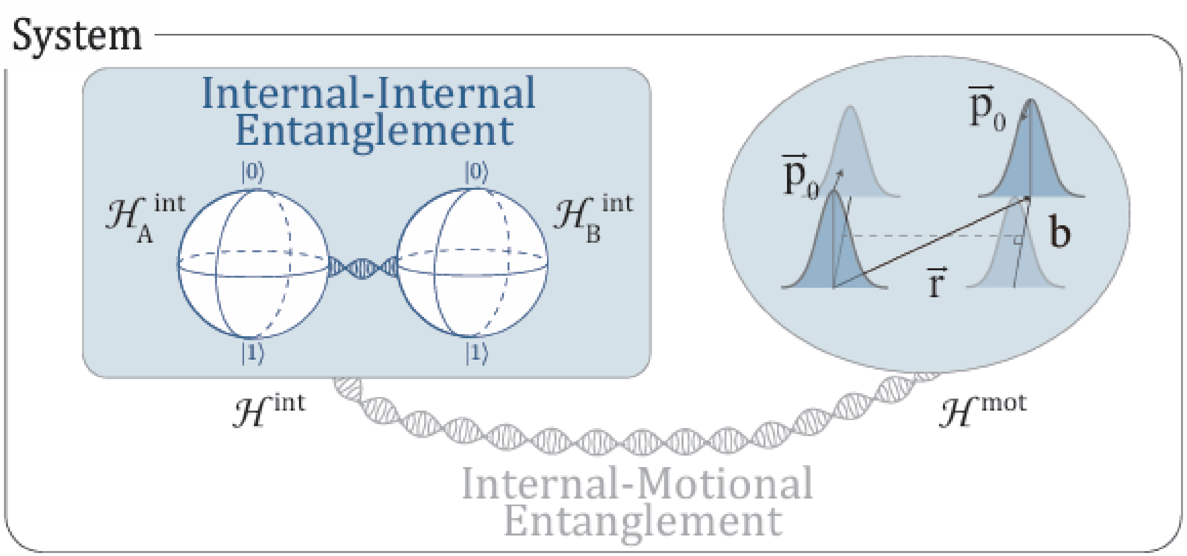
$$\rho_{\text{int}}^{(2)} = \frac{1}{4}\begin{pmatrix} 3 & \sqrt{3}\,\gamma^* \\ \sqrt{3}\,\gamma & 1 \end{pmatrix}$$

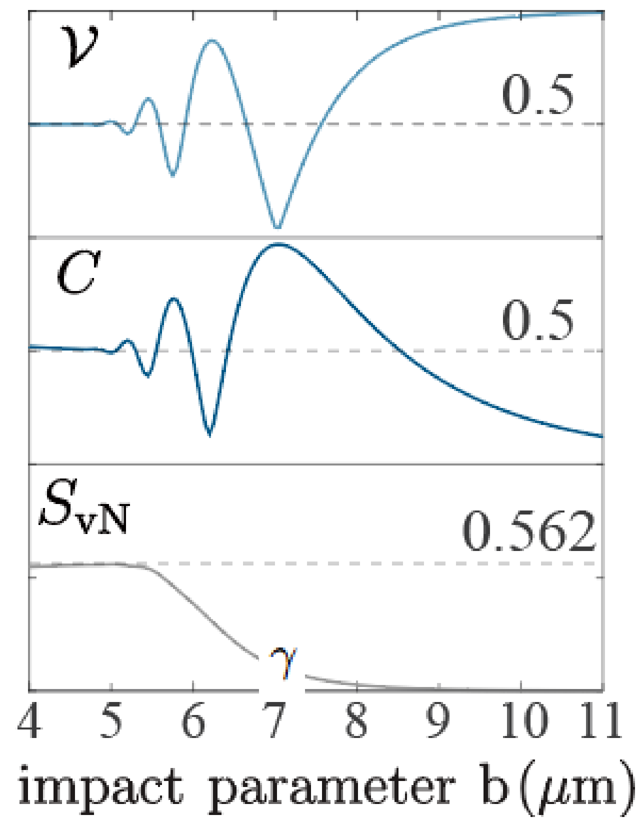
$$(i_A, i_B) \rightarrow \mathcal{C}(i_A, i_B)$$

$$(i_{AB}, m) \rightarrow S_{\text{vN}}(i, m)$$

$$|\chi_\perp\rangle = |\chi_{00}\rangle = |\chi_{01}\rangle = |\chi_{10}\rangle$$

Entanglements among Internals(A,B) and Motion





1. Internal (A) ↔ Internal (B) by $\mathcal{C}(i_A, i_B)$
2. Internal (A;B) ↔ Motional (r) by $S_{vN}(i, m)$

$\mathcal{V} = \frac{|1+\gamma|}{2}$ (experimental coherence)

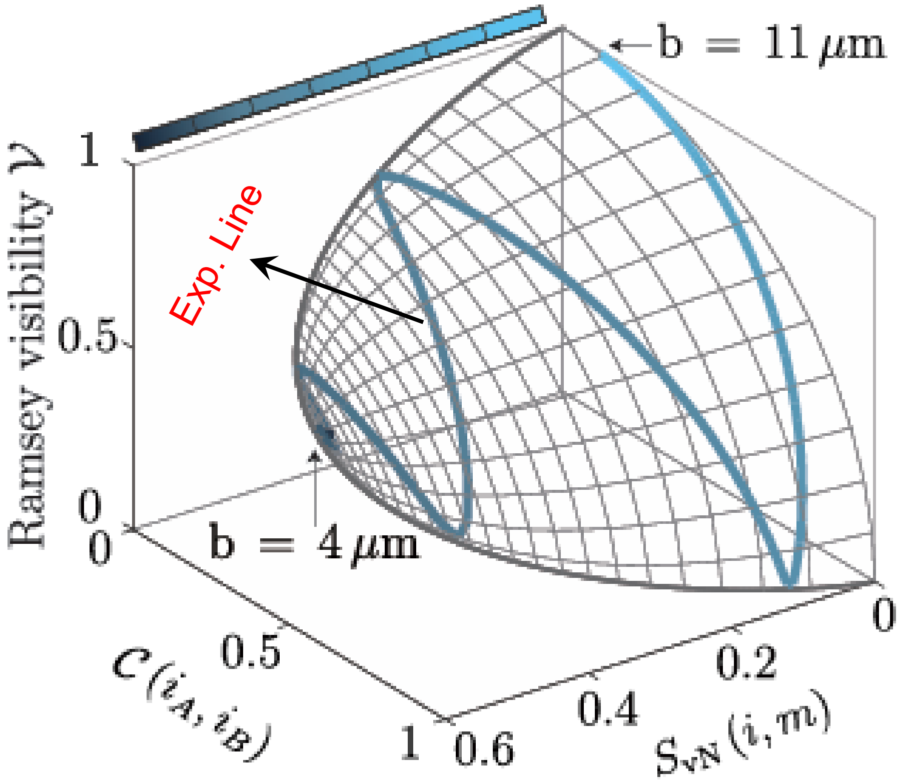
$C = \max\{0, \sqrt{\tilde{\lambda}_+} - \sqrt{\tilde{\lambda}_-}\}$ $\left(\tilde{\lambda}_\pm = \frac{|\gamma|^2 - 4\alpha + 3}{16} \pm \frac{\sqrt{2}}{8}\sqrt{(1-\alpha)(1-2\alpha+|\gamma|^2)}\ ,\ \alpha = \mathrm{Re}(\gamma) \right)$

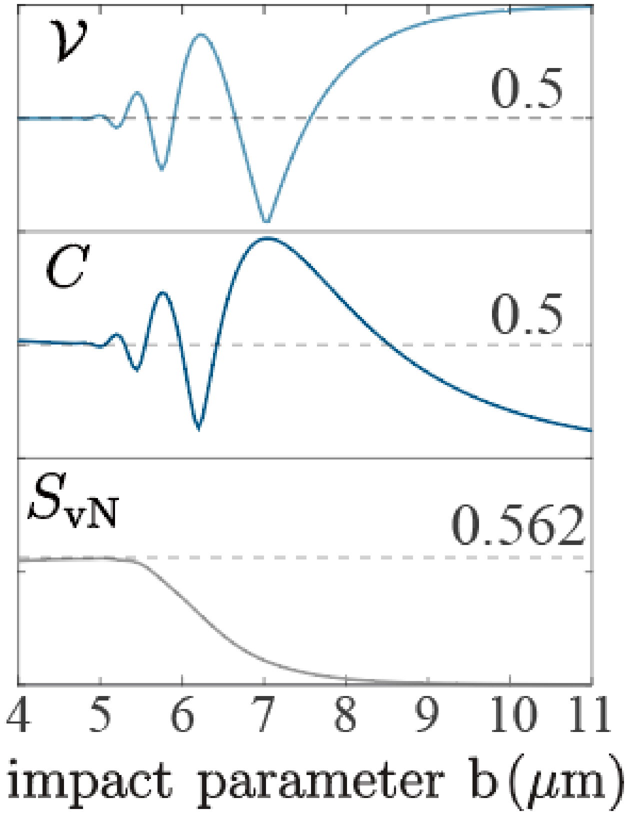
$S_{vN} = -\sum \lambda_\pm \log \lambda_\pm$ $\left(\lambda_\pm = \frac{1}{2} \pm \frac{1}{4}\sqrt{1+3|\gamma|^2} \right)$

All three quantities are governed by the same motional overlap

Entanglements among Internals(A,B) and Motion

Interplay between internal-internal (C or V)
and internal-motional (S) entanglements in Rydberg atom collision





Zero-temperature
Point Particle limit

Motional Overlap and Collision Regimes

Motional overlap

$$\gamma = \langle \chi_{\perp} | \chi_{11} \rangle = \int d\mathbf{r}\, \gamma(\mathbf{r})$$

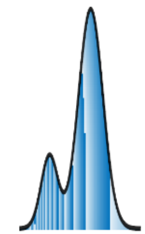
$$R_0 = \sqrt[5]{15\pi C_6 / 8\sqrt{2}\hbar v_{\rm rel}}$$

$$|\gamma| \simeq \exp\left[- \left(\frac{R_0^{10} \sigma_r^2}{b^{12}} \right) \right]$$

Motionally distinguishabile

Motionally indistinguishabile

Strong Collision
$\gamma \ll 1$

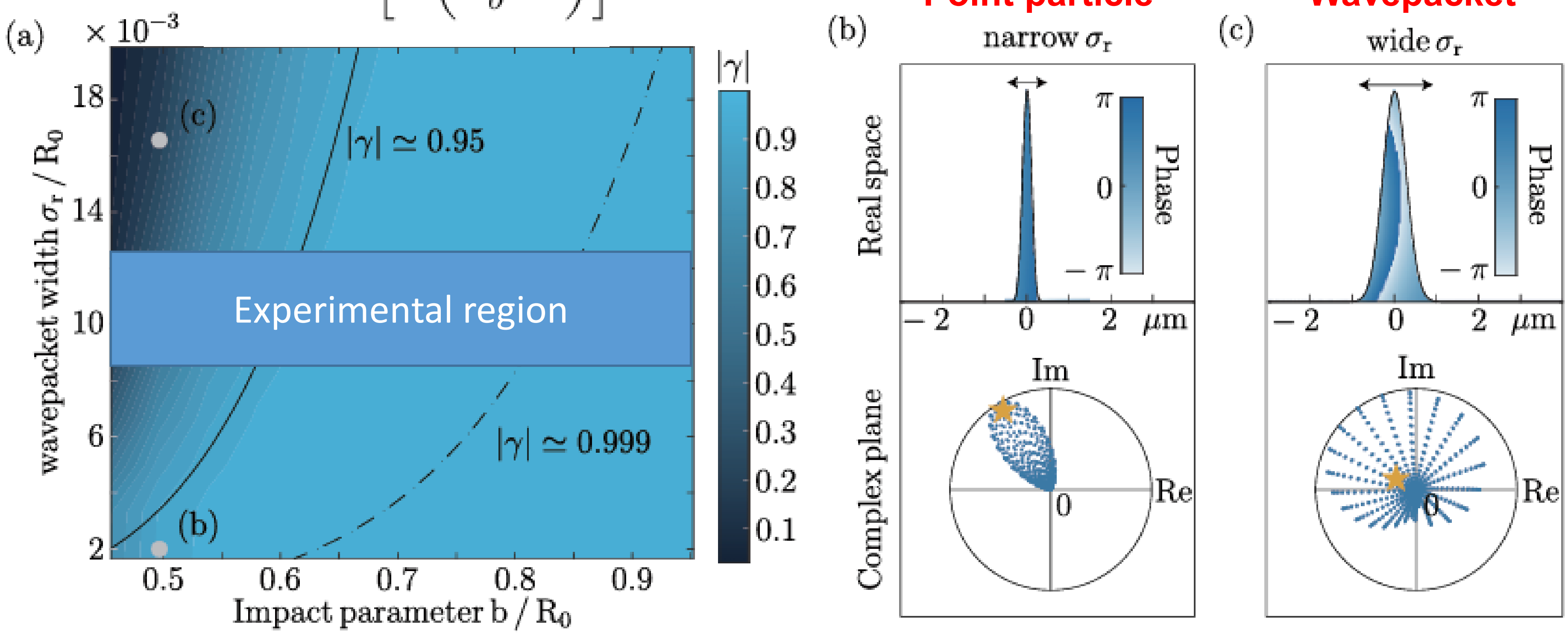


Fly-by interaction

Intermediate regime

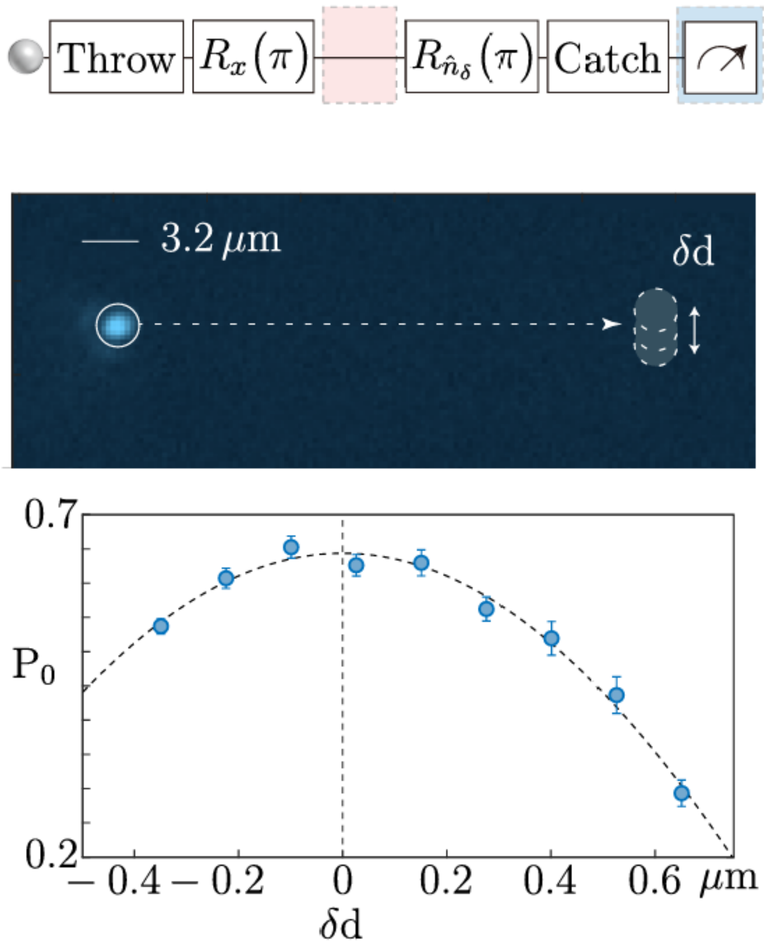
Point particle

Wavepacket

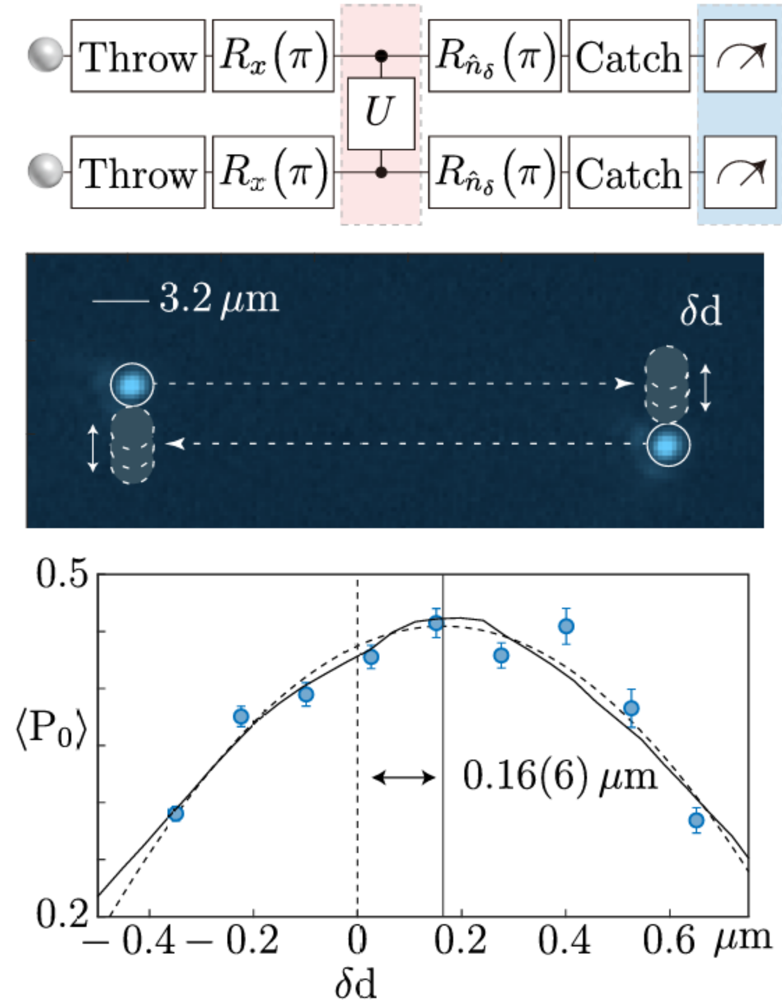


Strong Collision Region $\gamma = \langle \chi_\perp | \chi_{11} \rangle \ll 1$

Reference (no collision)

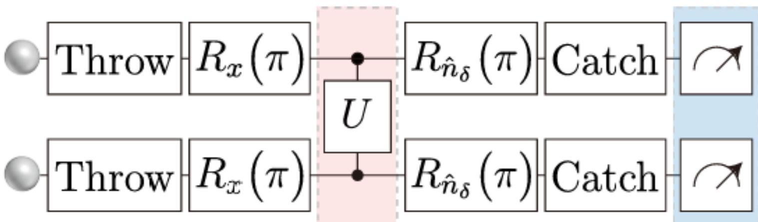


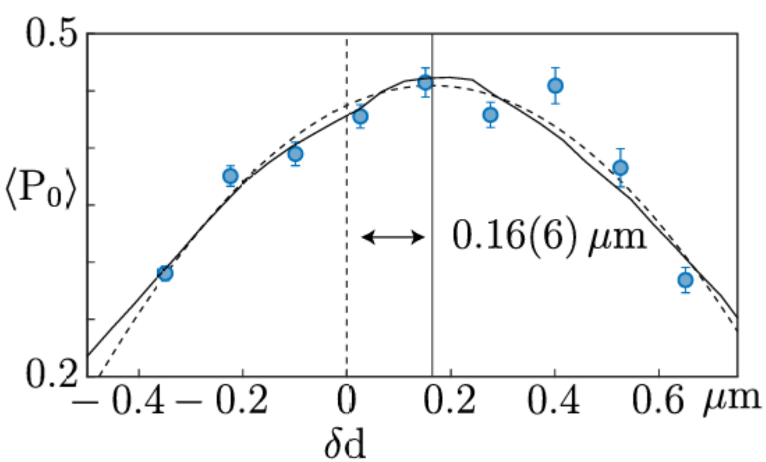
Collision channel



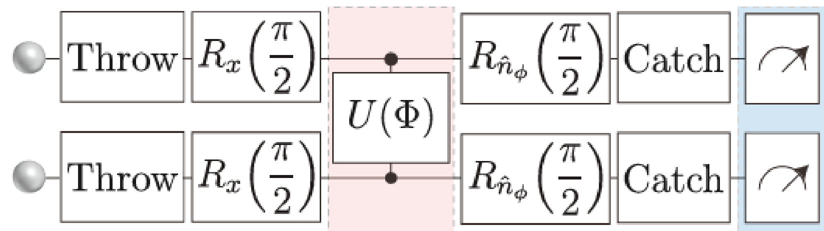
Controlled collision for Intermediate Regime

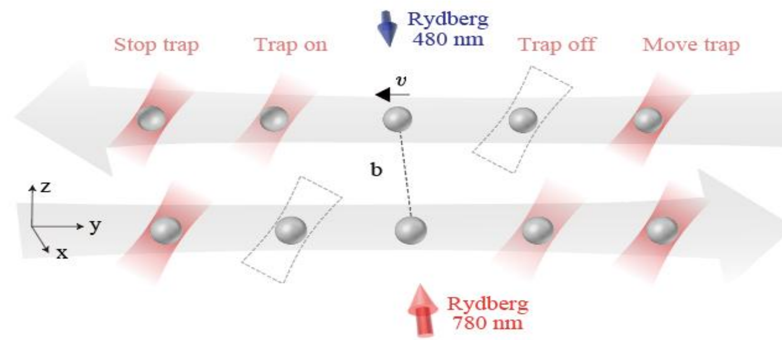
Rydberg-Rydberg collision

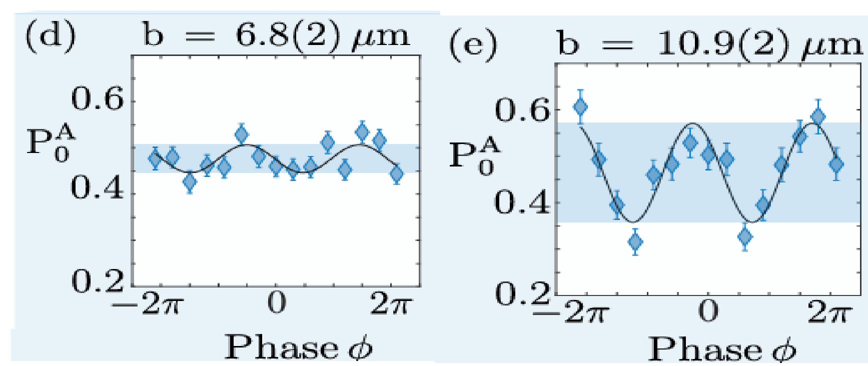




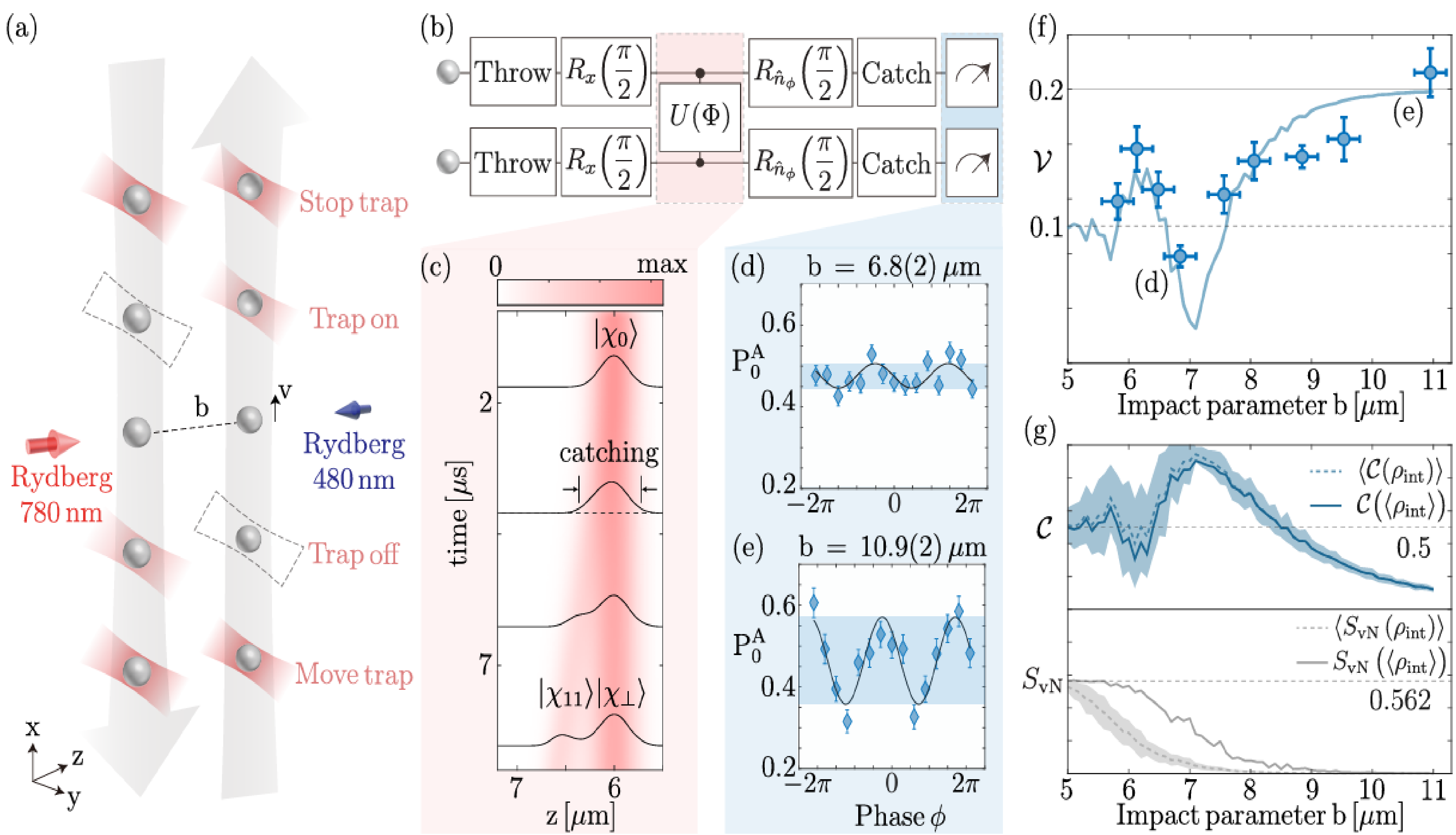
$|+\rangle - |+\rangle$ collision





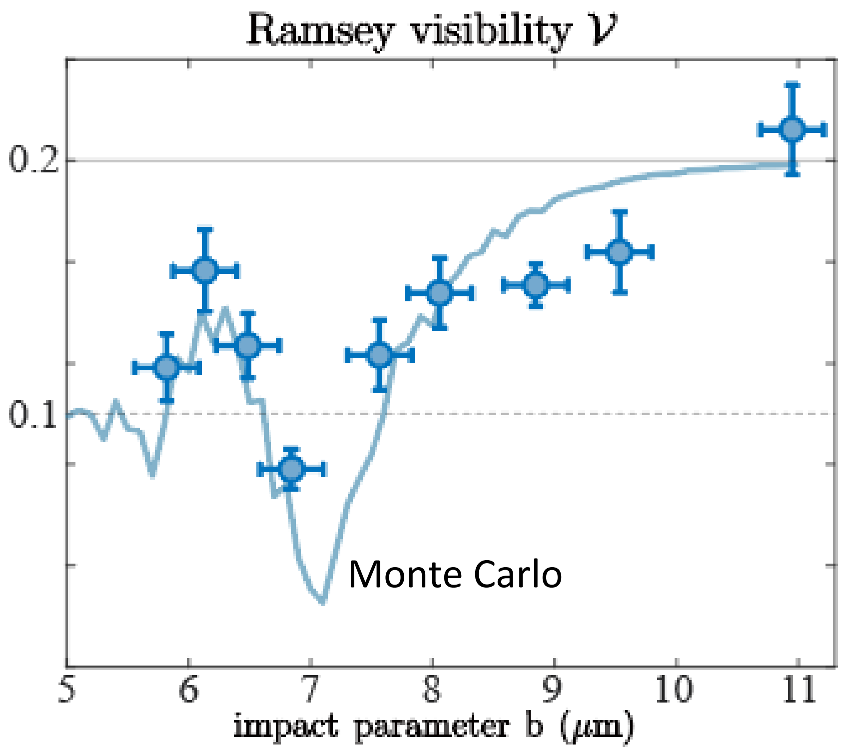


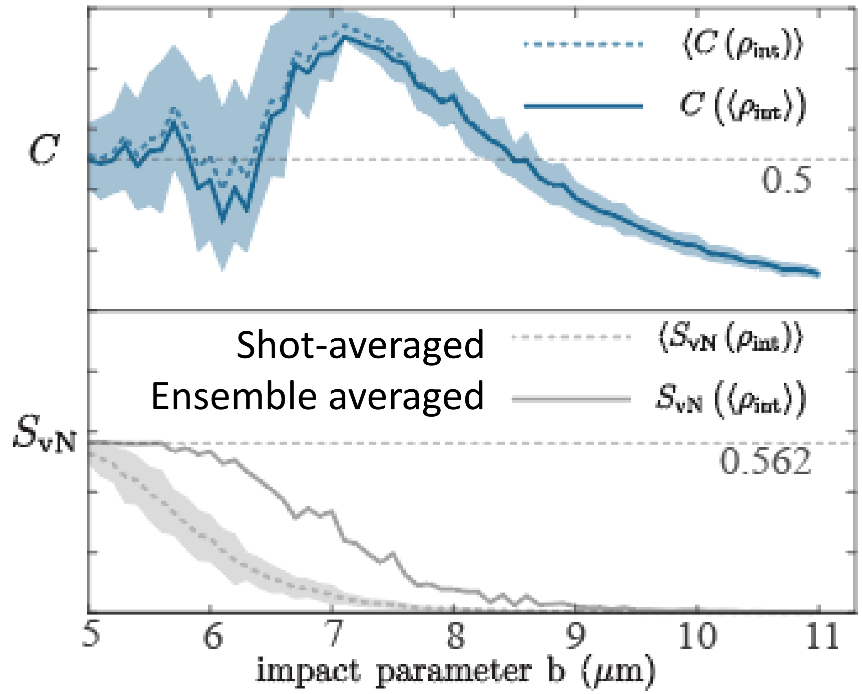
Ramsey Interferometry for Intermediate Regime



S. Hwang and H. Hwang et al., “Collision-Induced Entanglement in Two Flying Atoms," preprint (2026).

Ramsey Interferometry for Intermediate Regime



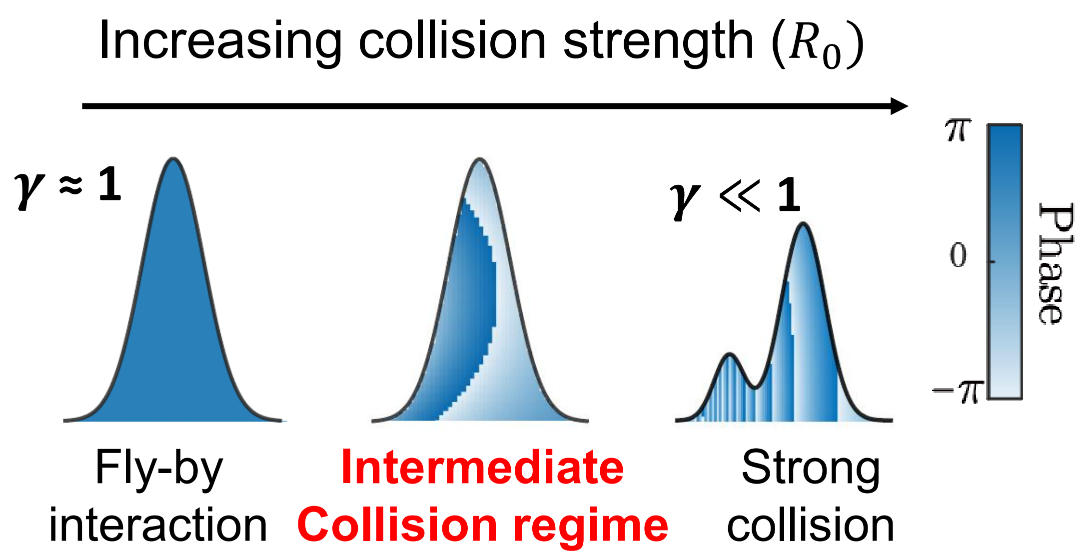


Incomplete recovery of Ramsey visibility indicates reduced motional overlap $|\gamma|$

Thermal averaging is included in concurrence (A,B) and von Neumann entropy (internal,motional)

Incomplete visibility recovery is coupled with motional distinguishability

Three Collision Regimes for $|+\rangle - |+\rangle$ collisions



Motional overlap

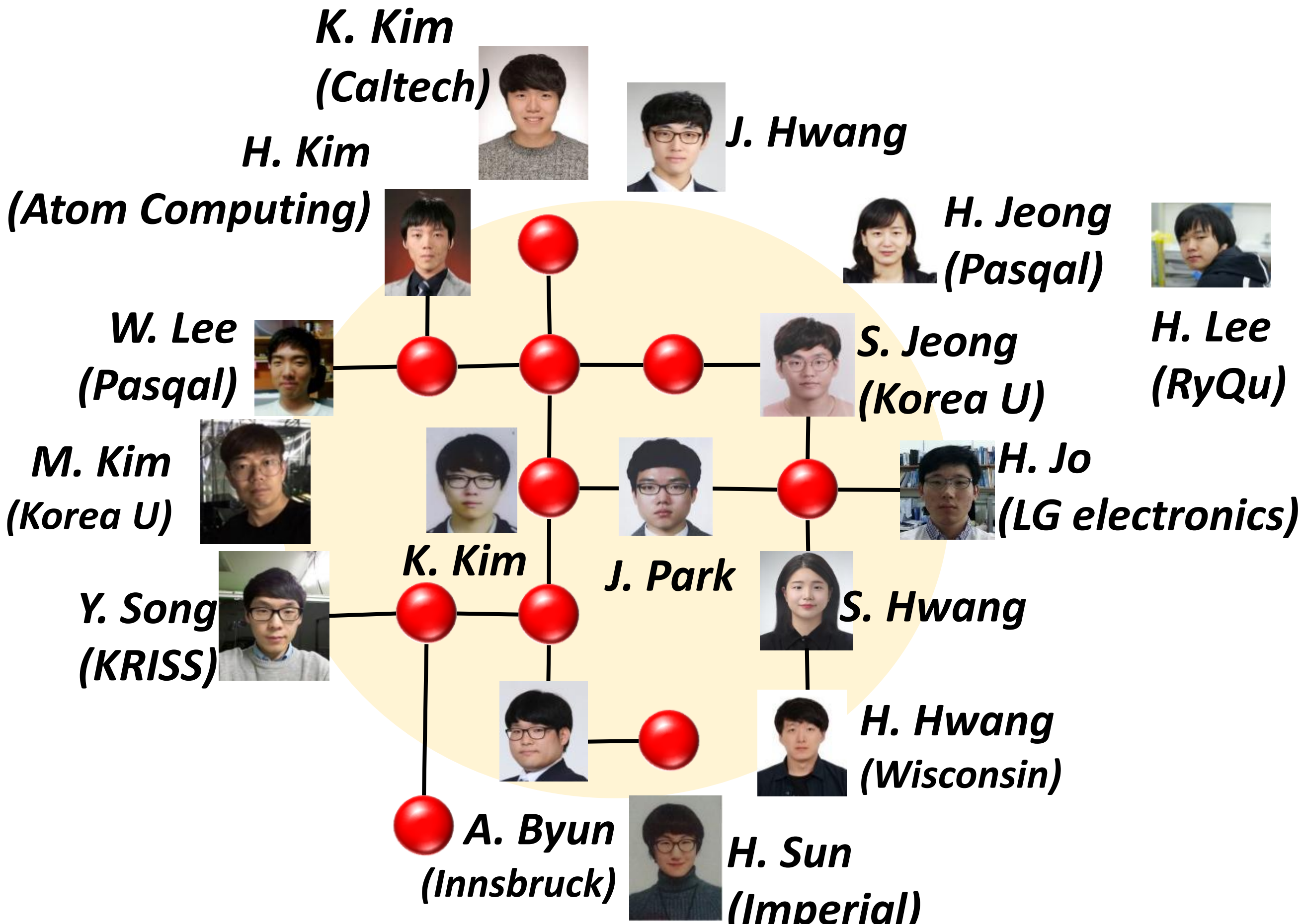
$$\gamma = \langle \chi_{\perp} | \chi_{11} \rangle = \int d\mathbf{r}\, \gamma(\mathbf{r})$$

- Weak interaction → motion degree indistinguishable
  → high internal coherence
- Strong collision → motion degree distinguishable
  → reduced internal coherence

Motional degree distinguishability ↓

→ reduced internal coherence

Rydberg Quantum Computing Team at KAIST



Funded by

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