Dynamics Of Atoms Within Atoms

S. Tiwari[1], F. Engel[2], M. Wagner[3], R. Schmidt[3], F. Meinert[2], and S. Wüster[1]

[1]Department of Physics, Indian Institute of Science Education and Research, Bhopal, Madhya Pradesh 462023, INDIA

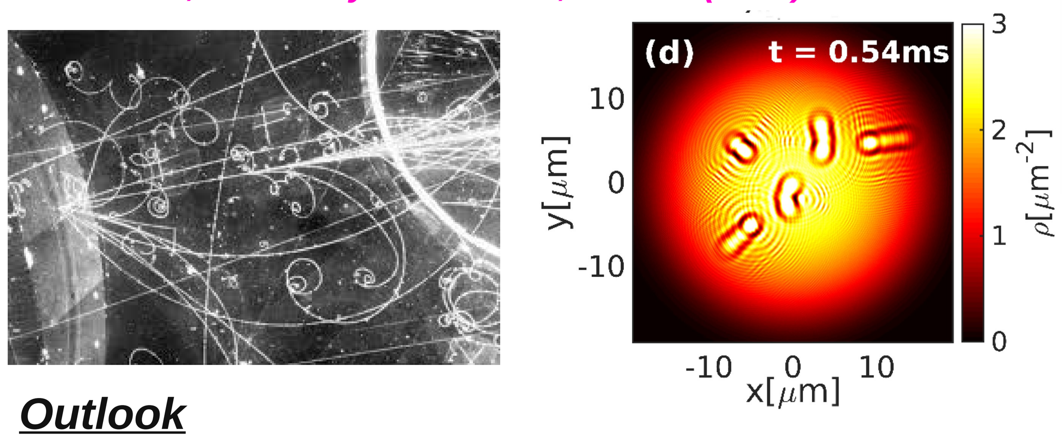
[2]Physikalisches Institut and Center for Integrated Quantum Science and Technology, Universität Stuttgart, Pfaffenwaldring 57, 70569 Stuttgart, Germany

[3]Max-Planck-Institut für Quantenoptik, 85748 Garching, Germany

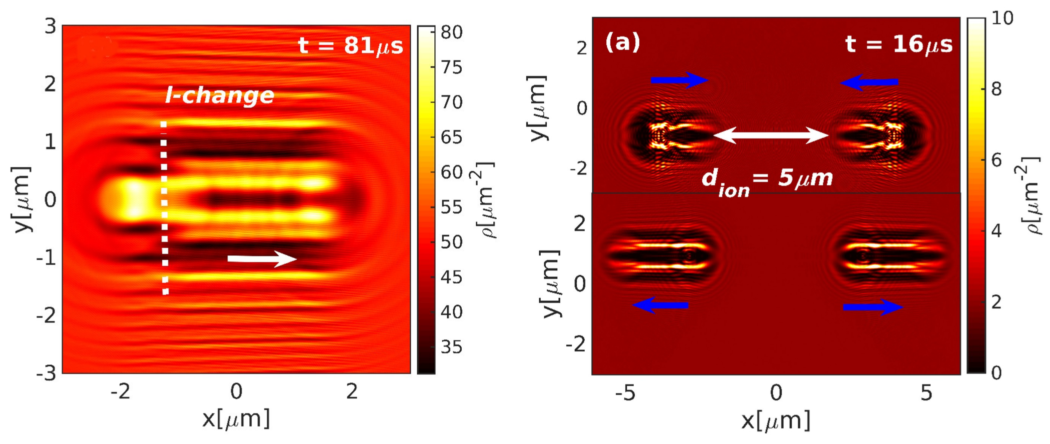
"Rydberg" bubble chamber

Tracking Rydberg atoms with Bose-Einstein condensates

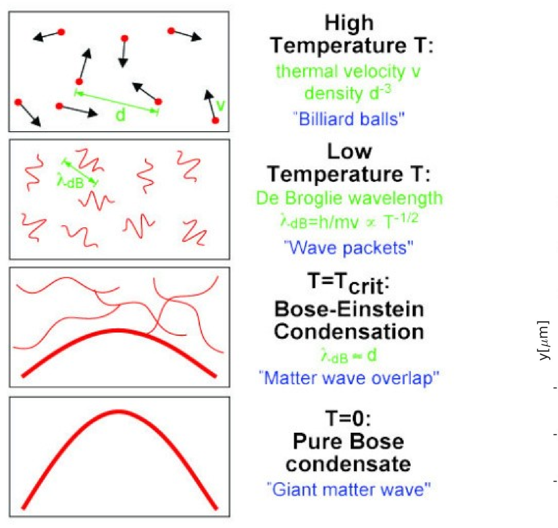
S. K. Tiwari, et. al. Phys. Rev. A 99, 043616 (2019).



Outlook

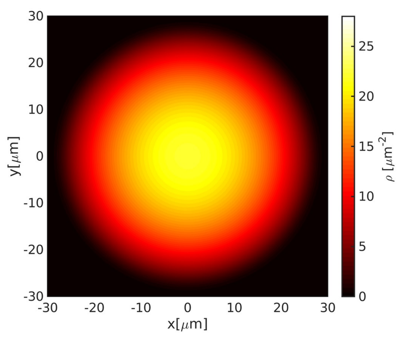


Bose-Einstein condensate (BEC)



- Condensate atoms

$$N_0 = N\left[1 - \frac{T}{T_c}^{\alpha}\right]$$

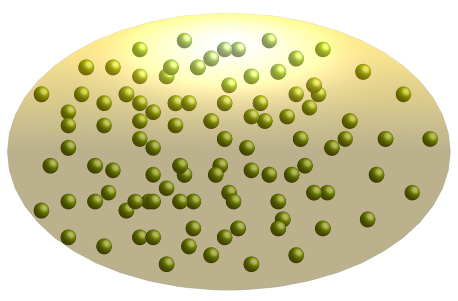


Gross-Pitaevskii equation (GPE)

- Hamiltonian of BEC with effective interaction between ground state atoms[1]

$$\hat{H}_0 = \sum_{n=1}^{N}\left[-\frac{\hbar^2}{2m}\nabla_n^2 + W(\mathbf{R}_n)\sigma_{gg}^{(n)}\right] + g_{3D}\sum_{n>m}\delta(\mathbf{R}_n - \mathbf{R}_m)\sigma_{gg}^{(n)}\sigma_{gg}^{(n)}$$

$$g_{3d} = \frac{4\pi^2 a_s}{M}$$



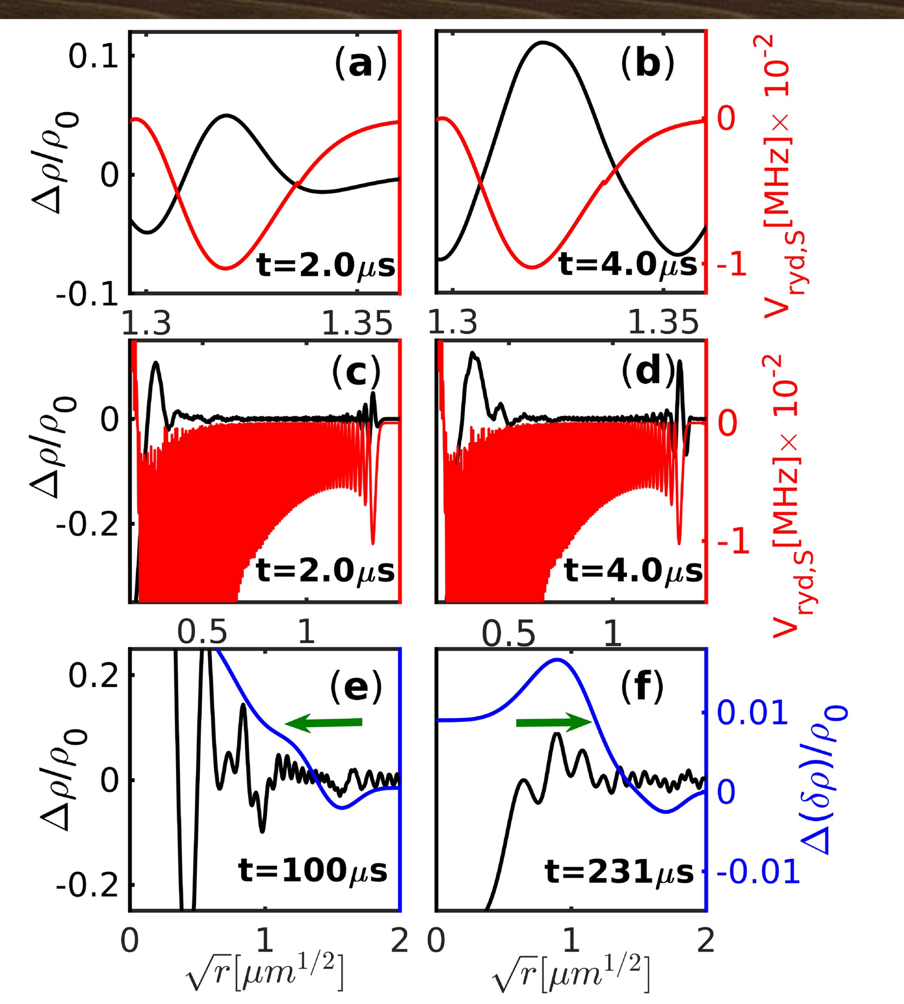
- Wavefunction of BEC

$$\Psi(\mathbf{R}_1, \mathbf{R}_2, ...\mathbf{R}_n) = \prod_n^N \psi(\mathbf{R}_n)$$

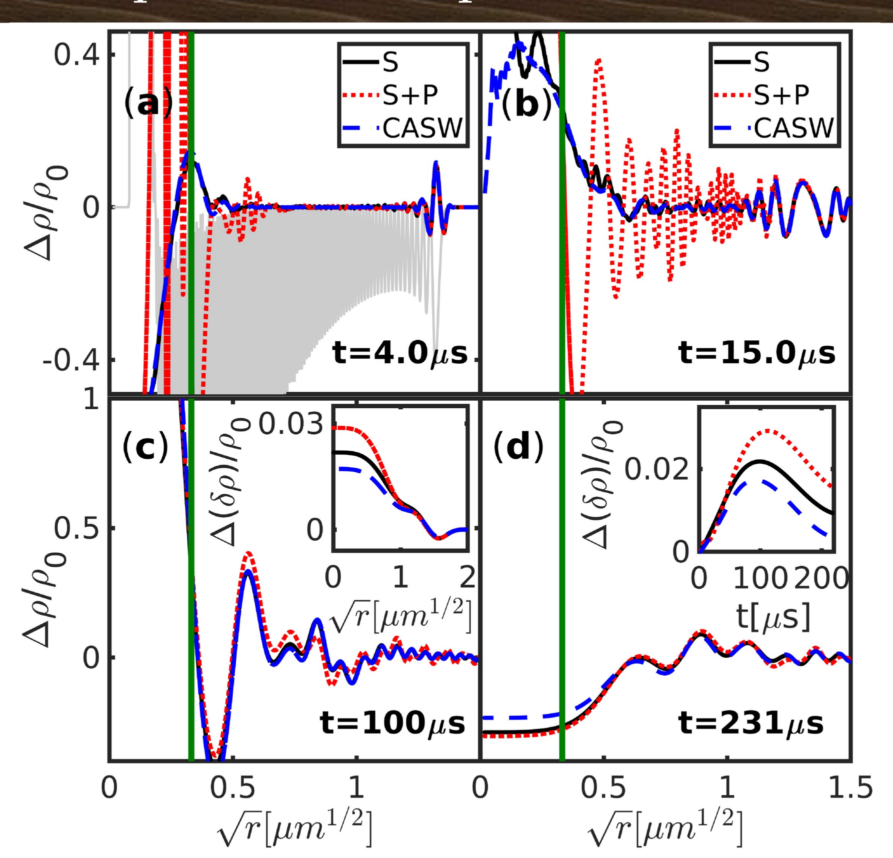
- Time dependent Gross-Pitaevskii equation (GPE)

$$i\hbar\frac{\partial}{\partial t}\phi(\mathbf{R}) = \left(-\frac{\hbar^2}{2m}\nabla^2 + W(\mathbf{R}) + g_{3D}|\phi(\mathbf{R})|^2\right)\phi(\mathbf{R})$$

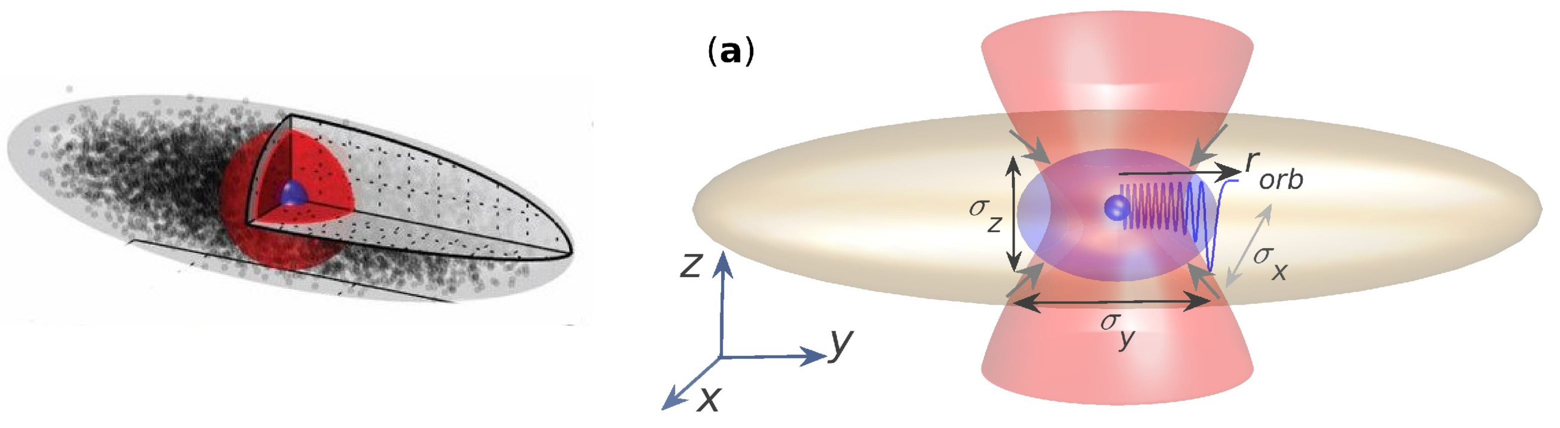
Single spherical excitation



Dependence on potential details



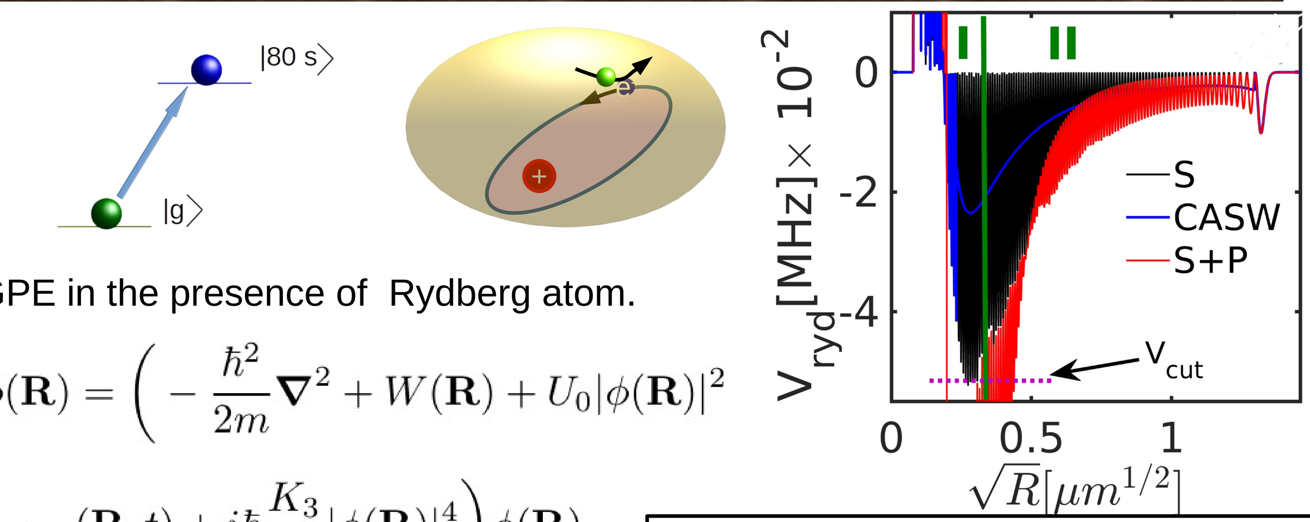
Motivation



J. B. Balewski, et. al. Nature 502, 664 (2013). *S. Tiwari, et. al. arXiv:2111.05031.*

- Interaction of a single localized electron of Rydberg atom with BEC can set the whole condensate in a collective oscillation.

Interaction between Rydberg atom and BEC



- 3D-GPE in the presence of Rydberg atom.

$$i\hbar\frac{\partial}{\partial t}\phi(\mathbf{R}) = \left(-\frac{\hbar^2}{2m}\nabla^2 + W(\mathbf{R}) + U_0|\phi(\mathbf{R})|^2 + V_{\mathrm{ryd,S,n}}(\mathbf{R},t) + i\hbar\frac{K_3}{2}|\phi(\mathbf{R})|^4\right)\phi(\mathbf{R}),$$

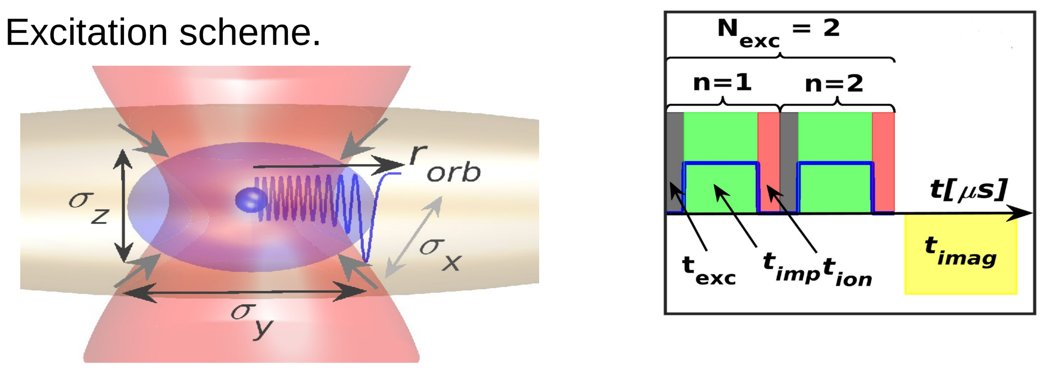
$$V_{\mathrm{ryd,S}}(\mathbf{R},t) = \eta(t)V_0(\mathbf{R})|\Psi(\mathbf{R}-\mathbf{x}_{n(t)})|^2$$

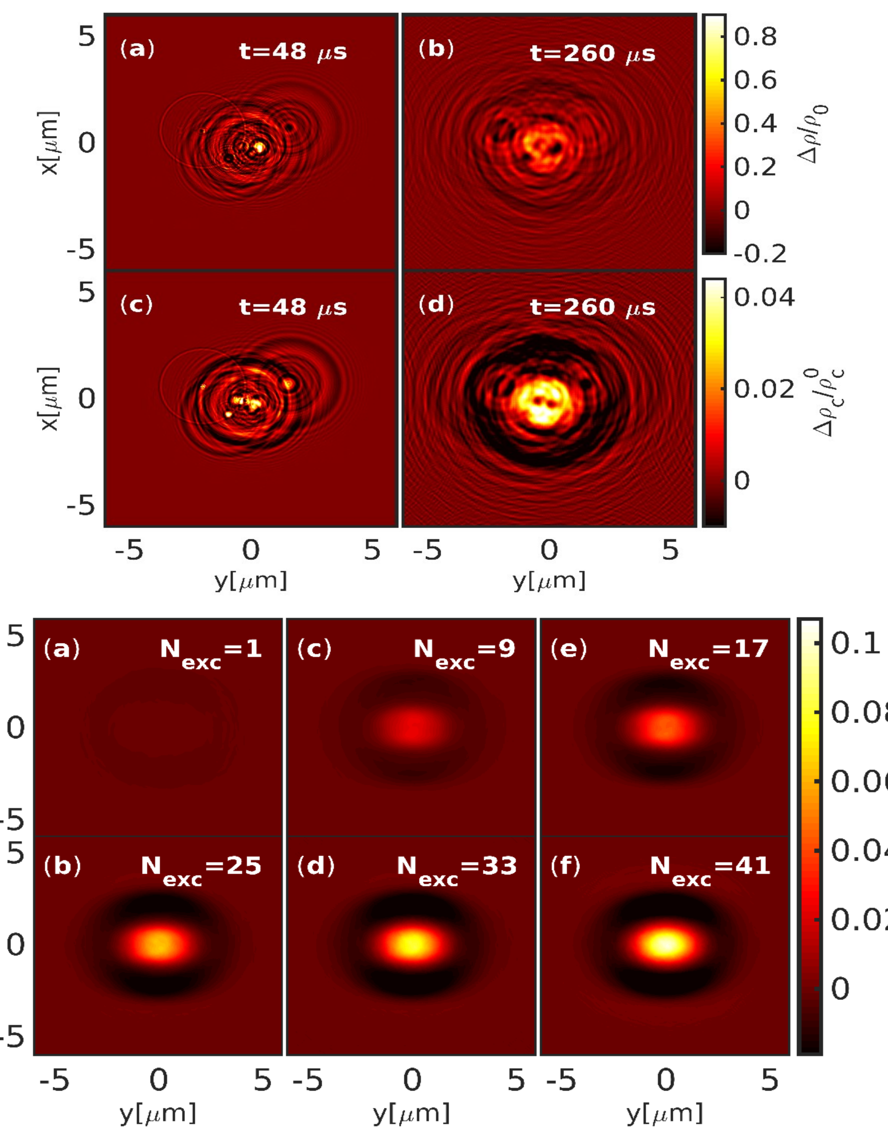
- Under the spherical symmetry.

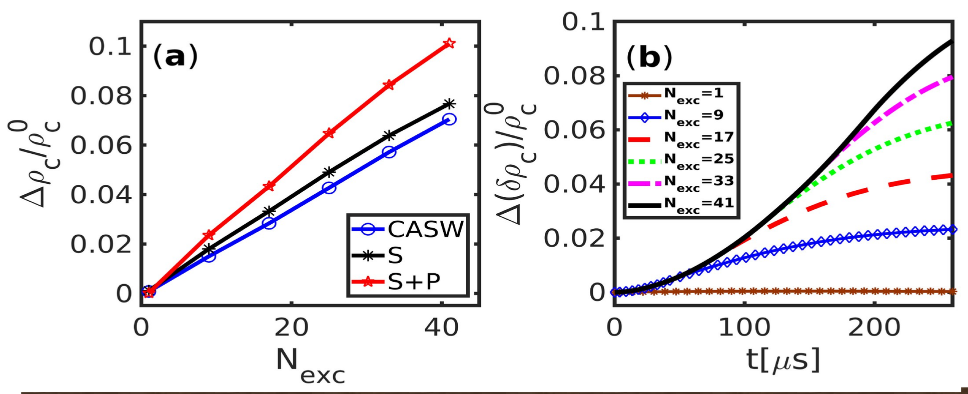
$$i\hbar\frac{\partial}{\partial t}u(r,t) = -\frac{\hbar^2}{2m}\frac{\partial^2 u(r,t)}{\partial r^2} + \frac{U_0}{r^2}|u(r,t)|^2 u(r,t) + V_{\mathrm{ryd,S,n}}(r)u(r,t),$$

Repeat Excitations

- Excitation scheme.







Condensate heating

- We use truncated Wigner approximation[5] to calculate condensate heating and did scaling for a single impurity moving through a dense BEC.
- Initial stochastic field

$$\alpha(\mathbf{R},0) = \phi_0 + \sum_k[\eta_k u_k(\mathbf{R}) - \eta_k^* v_k^*(\mathbf{R})]/\sqrt{2}.$$

$$\overline{\eta_k\eta_l} = 0 \qquad \overline{\eta_k\eta_l^*} = \delta_{nl}$$

- Quantum correlations can be calulated using stochastic field

$$\frac{1}{2}\langle\hat{\Psi}^\dagger(\mathbf{R}')\hat{\Psi}(\mathbf{R}) + \hat{\Psi}(\mathbf{R})\hat{\Psi}^\dagger(\mathbf{R}')\rangle \rightarrow \overline{\alpha^*(\mathbf{R}')\alpha(\mathbf{R})}$$

- Total atom density

$$n_{tot}(\mathbf{R}) = \overline{|\alpha(\mathbf{R})|^2} - \frac{\delta_c}{2},$$

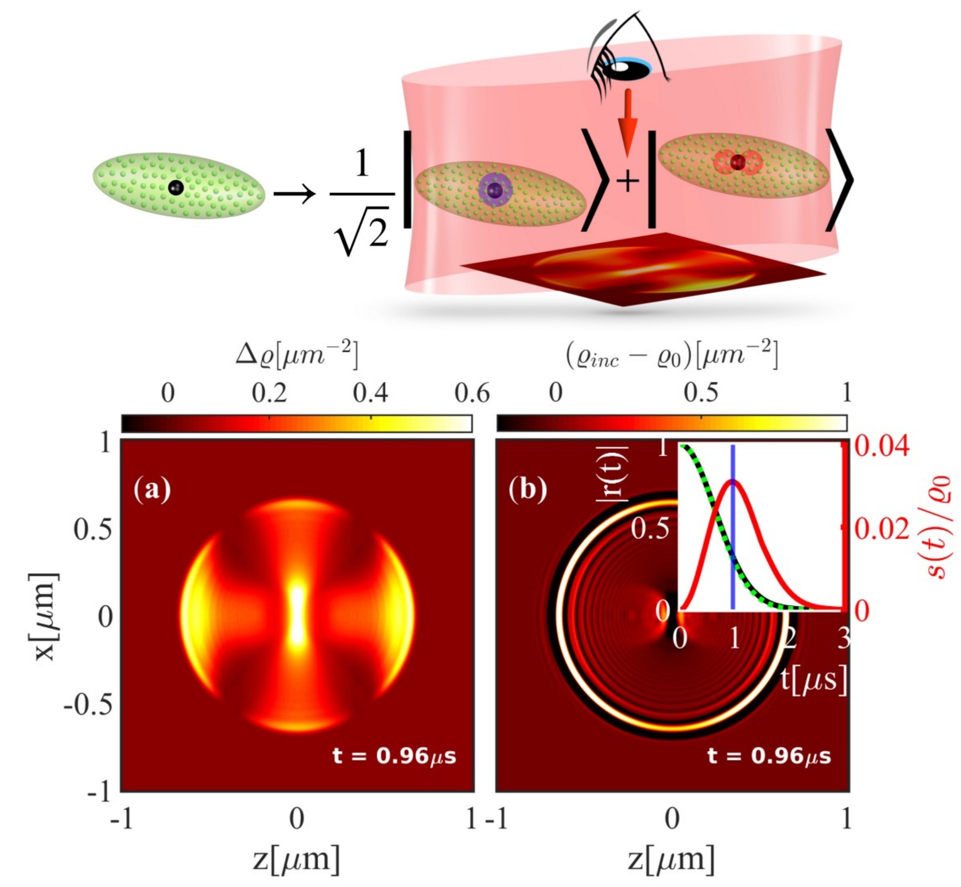
- Condensed density → $n_{cond}(\mathbf{R}) = \left|\overline{\alpha(\mathbf{R})}\right|^2$
- Uncondensed density → $n_{unc}(\mathbf{R}) = n_{tot}(\mathbf{R}) - n_{cond}(\mathbf{R})$

Extracting decoherence from environmental

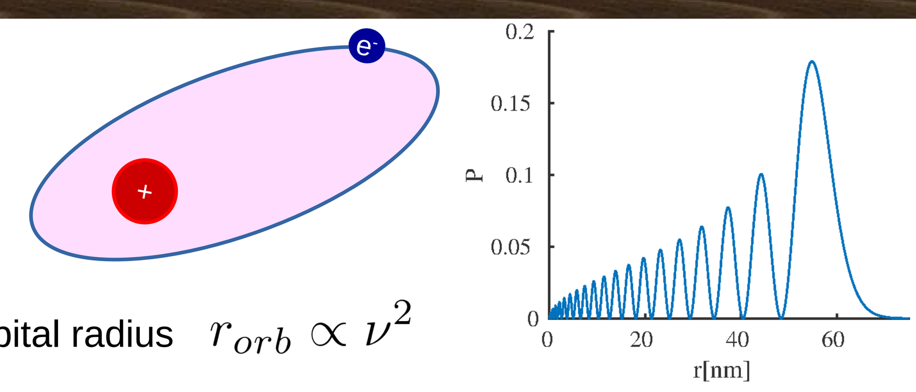
Imaging the interface of a qubit and its quantum-many-body environment

S. Rammohan, et. al. https://arxiv.org/abs/2011.11022 (2020)

Poster 11: *Sidharth Raamohan*



Rydberg atom



- Orbital radius $r_{orb} \propto \nu^2$

Interaction potentials

- We compare three different intraction potentials,

s-wave[2]:

$$V_{\mathrm{ryd,S}}(\mathbf{R},t) = \eta(t)V_0(\mathbf{R})|\Psi(\mathbf{R}-\mathbf{x}_{n(t)})|^2$$

s+p-wave[3]:

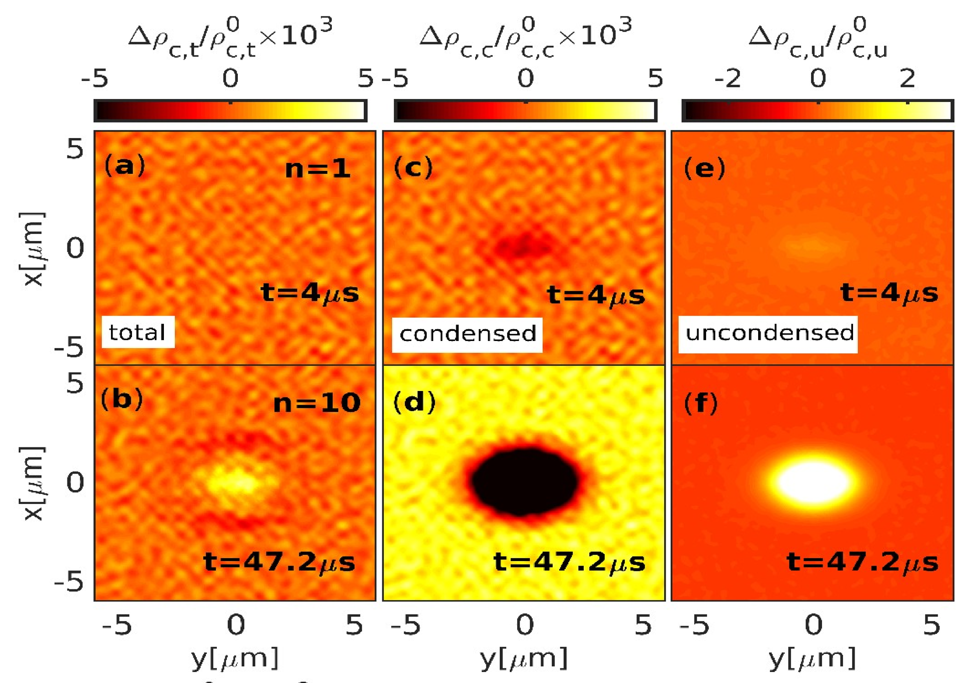
$$V_{\mathrm{ryd,s+p,n}}(\mathbf{R},\mathbf{r},t) = \eta(t)\Big|V_0(\mathbf{R})\delta^{(3)}(\mathbf{R}-\mathbf{x}_n(t)-\mathbf{r}) + \frac{6\pi\hbar^2 a_p[k(\mathbf{R})]}{m_e}\delta^{(3)}(\mathbf{R}-\mathbf{x}_n(t)-\mathbf{r})\overleftarrow{\nabla}_\mathbf{r}\cdot\overrightarrow{\nabla}_\mathbf{r}\Big|,$$

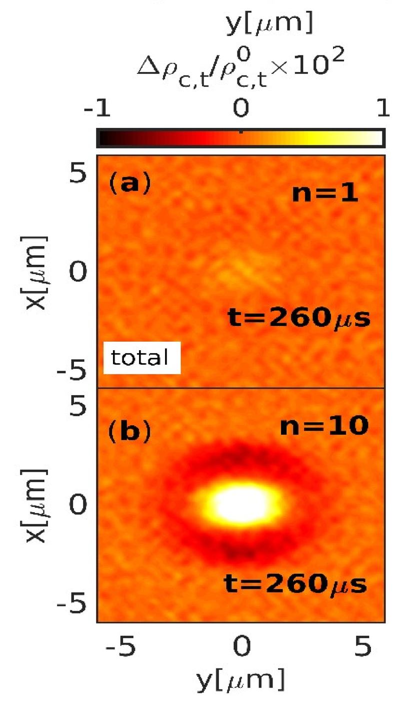
Classical approximation of s-wave (CASW)[4]

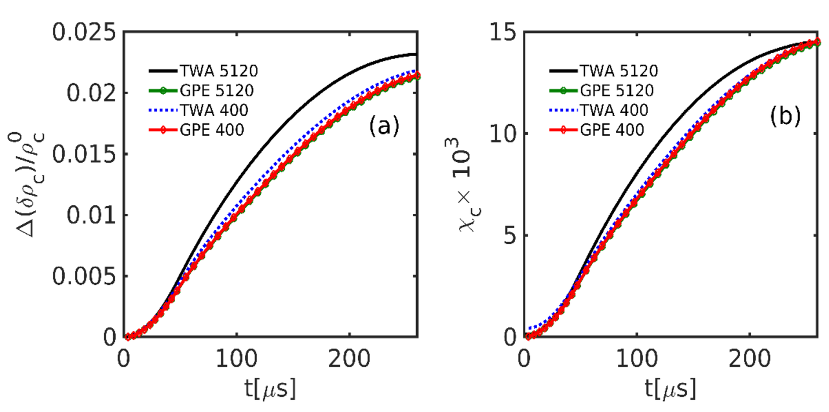
$$V_c(\mathbf{R},t) = \eta(t)V_0(\mathbf{R})\begin{cases}\rho^Q(\mathbf{R}) & R < R_{\min}/2,\\ \rho^{\mathrm{cl}}(\mathbf{R}) & R_{\min}/2 < R < R_{\mathrm{ct}}\\ \rho^Q(\mathbf{R}) & R \geq R_{\mathrm{ct}},\end{cases}$$

$$\rho^{\mathrm{cl}}(\mathbf{R}) = \frac{1}{8\pi^2 R}\frac{1}{\sqrt{\epsilon^2 b^2 - (R-b)^2}}$$

Condensate heating







References

[1] C. J. Pethik and H. Smith, *Bose-Einstein condensation in dilute gases* (Cambridge University Press, 2002).
[2] E. Fermi, et al. **11**, 157 (1934).
[3] Omont, A., J. Phys. France **38**, 1343 (1977).
[4] A. Martin-Ruiz, et al. Journal of Modern Physics **4**, 818 (2013).
[5] A. A. Norrie, Ph.D. thesis, University of Otago (2005).
[6] S. Tiwari, et. al. arXiv:2111.05031.