Title: Rydberg atoms in Bose-Einstein condensed environments: cold bubble chambers and mesoscopic entanglement

Speakers: Sebastian WÃ¼ster

Collection: Cold Atom Molecule Interactions (CATMIN)

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Abstract: "S. Tiwari, S. Rammohan, A. Mishra, A. Pendse, A. K. Chauhan, R. Nath, F. Engel, M. Wagner, R.Schmidt, F. Meinert, A. Eisfeld and S. Wüster

Indian Institute of Science Education and Research, Bhopal India Palacký University, Olomouc, Czech Republic Indian Institute of Science Education and Research, Pune, India Max Planck Institute for the Physics of Complex Systems, Dresden, Germany Universität Stuttgart, Germany Max-Planck-Institute of Quantum Optics and MCQST, Garching, Germany

Rydberg Atoms in highly excited electronic states with n=30-200 can be excited within BoseEinstein condensates (BECs), and while lifetimes are shorter than in vacuum [1,2], they live long enough to cause a response of the BEC mean field [3]. During this, thousands of ground-state atoms are present within the Rydberg orbit, allowing the study of atoms moving within atoms [4]. We present beyond-mean field models of the joint Rydberg-BEC dynamics, showing how either
can be used to probe the other.

For multiple Rydberg atoms in a single electronic state, we show that the phase coherence of thecondensate allows the tracking of mobile Rydberg impurities akin to the function of bubblechambers in particle physics [5]. For a single Rydberg atom with multiple electronic states, weprovide spectral densities of the BEC as a decohering environment [6], and show that the BECcan image a signature of the entangling evolution that causes Rydberg q-bit decoherence [7] or
serve as non-Markovian environment for quantum simulations.

[1] Schlagmu?ller et al. PRX 6 (2016) 031020.
[2] Kanungo et al. PRA 102 (2020) 063317.
[3] Balewski et al. Nature 502 (2013) 664.
[4] Tiwari et al. arXiv:2111.05031 (2021)
[5] Tiwari et al. PRA 99 (2019) 043616.
[6] Rammohan et al. PRA 103 (2021) 063307.
[7] Rammohan et al. PRA(Letters) 104 (2021) L060202."

Rydberg atoms in Bose-Einstein condensed environments

from bubble chambers to paradigmatic open quantum systems

Sebastian Wüster

Department of Physics
Indian Institute of Science Education and Research Bhopal, India

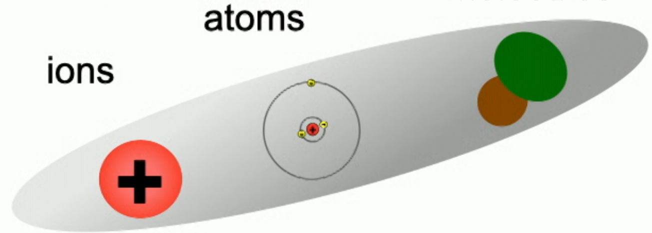
MPG-Partnergroup with:

Max-Planck Institute for the Physics of Complex Systems, Dresden, Germany

Geography

Ultra-cold and Rydberg atoms in Bhopal:
Max-Planck-IISER Partner Group

Cold Atom Molecule Interactions



Cold Atom Molecule Interactions

Ion-Rydberg molecules

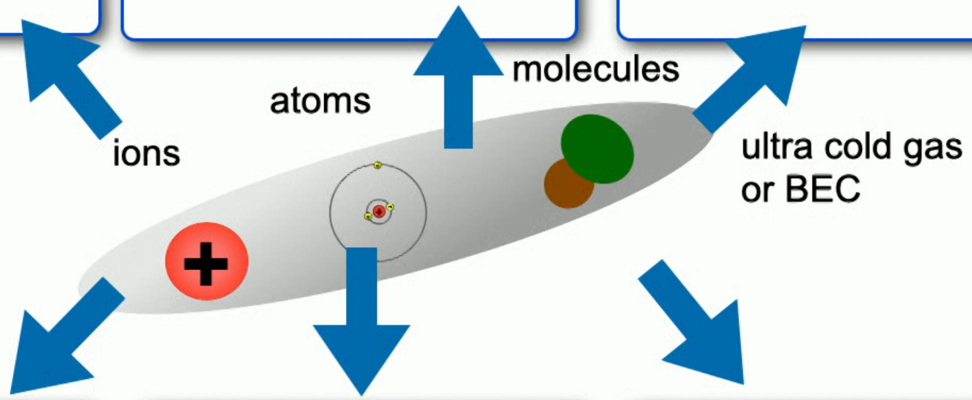
Zuber *et al.*
Nature **5** 453 (2022)

Rydberg polarons

F. Carmargo *et al.*,
PRL **120** (2018) 083401.

Ultra-long-range Mols

C.H. Greene *et al.*,
PRL **85** (2000) 2458.



Cold ion-atom scattering

e.g. S. Dutta and S. Rangwala
PRA(R) **97** (2018) 041401

Polaron formation

e.g. C. Kohstall *et al.*
Nature **485** (2012) 615

Angular momentum dynamics

e.g. Schmidt and Lemeshko
PRX **6** (2016) 011012

Origin of decoherence

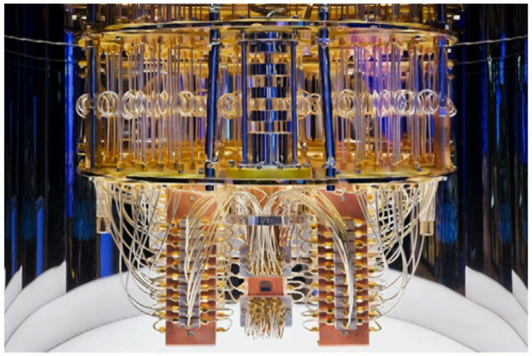
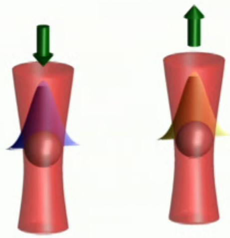


image: **IBM**



Qubit: $|\phi\rangle = c_0|0\rangle + c_1|1\rangle$

Origin of decoherence

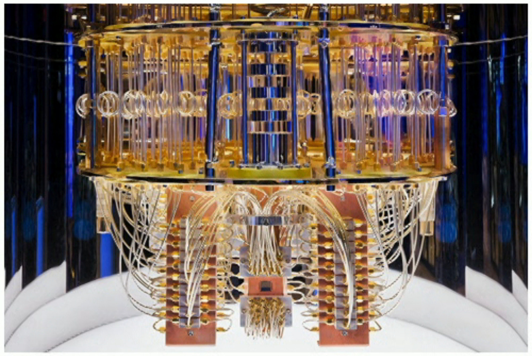
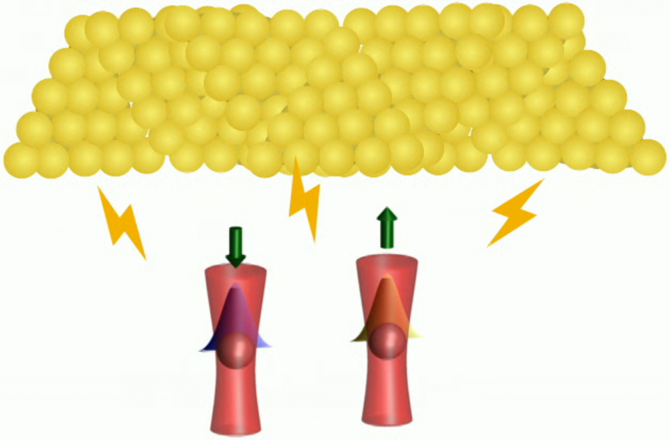


image: **IBM**



Qubit: $|\phi\rangle = c_0|0\rangle + c_1|1\rangle$

Qubit + Env: $|\chi\rangle = (c_0|0\rangle + c_1|1\rangle) \otimes |\Psi_{ini}\rangle$

Interaction: $\hat{H}_{int} = |0\rangle\langle 0| \otimes \hat{h}_0 + |1\rangle\langle 1| \otimes \hat{h}_1$

Origin of decoherence

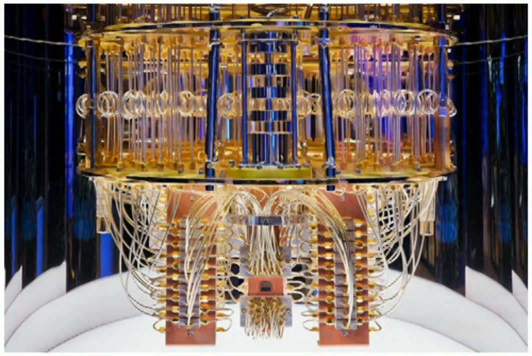
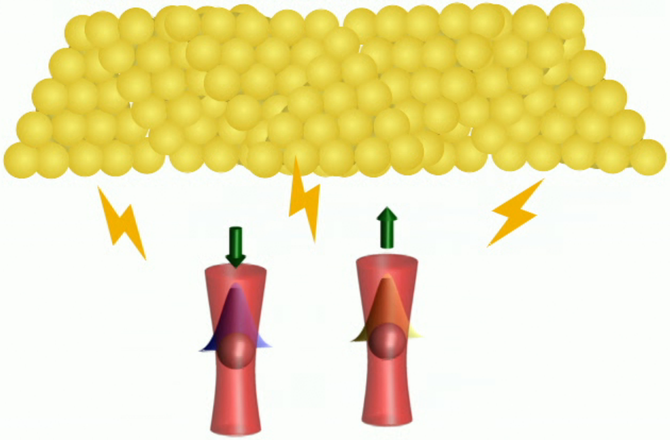


image: **IBM**



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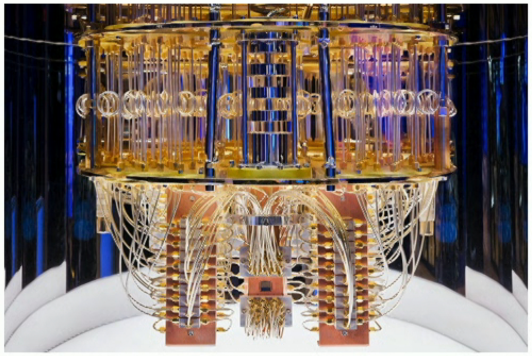
Entanglement
⇒ decoherence: $|\chi\rangle = c_0|0\rangle \otimes |\Psi_0\rangle + c_1|1\rangle \otimes |\Psi_1\rangle$

Origin of decoherence



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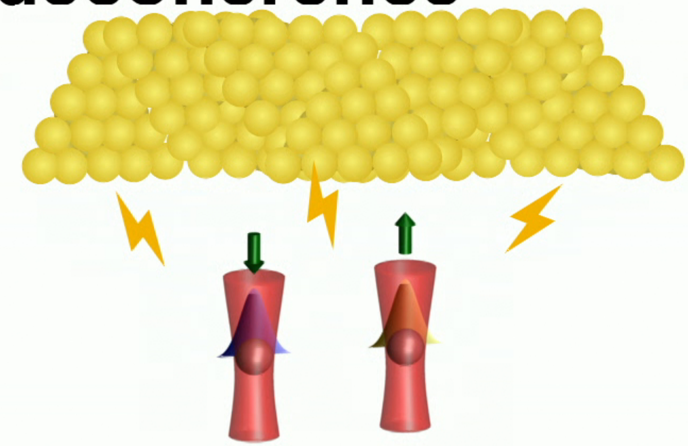
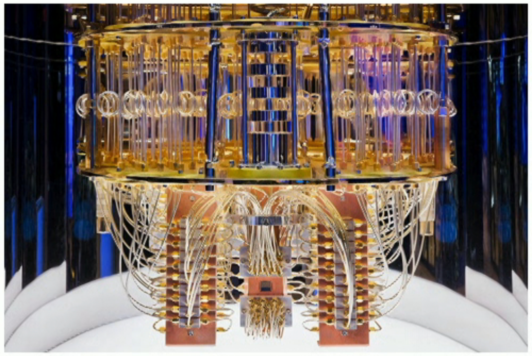


Qubit+ Environment: $|\chi\rangle = c_0|0\rangle \otimes |\Psi_0\rangle + c_1|1\rangle \otimes |\Psi_1\rangle$

Origin of decoherence



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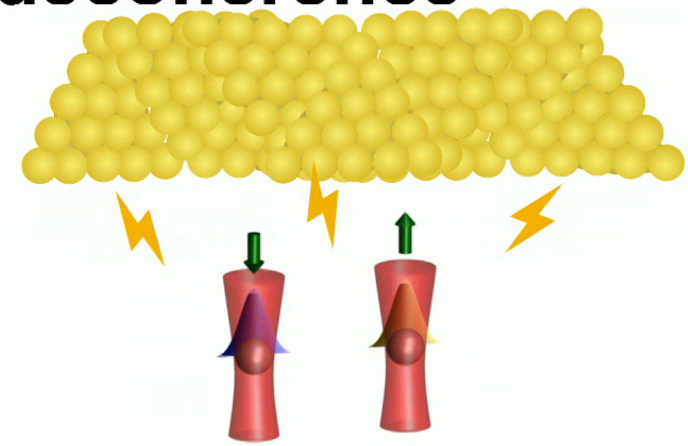


Qubit+ Environment: $|\chi\rangle = c_0 |0\rangle \otimes |\Psi_0\rangle + c_1 |1\rangle \otimes |\Psi_1\rangle$

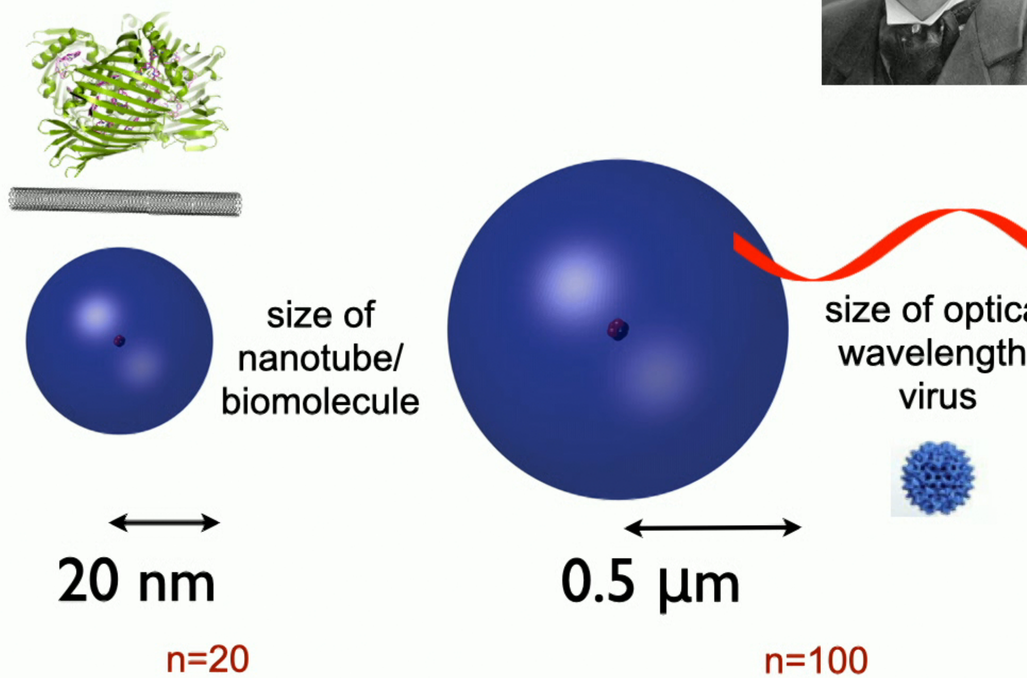
Reduced Qubit: $\hat{\rho} = \begin{pmatrix} |c_0|^2 & c_1 c_0^* \langle \Psi_0 | \Psi_1 \rangle \\ c_1^* c_0 \langle \Psi_1 | \Psi_0 \rangle & |c_1|^2 \end{pmatrix}$

Rydberg atoms

What are Rydberg atoms?

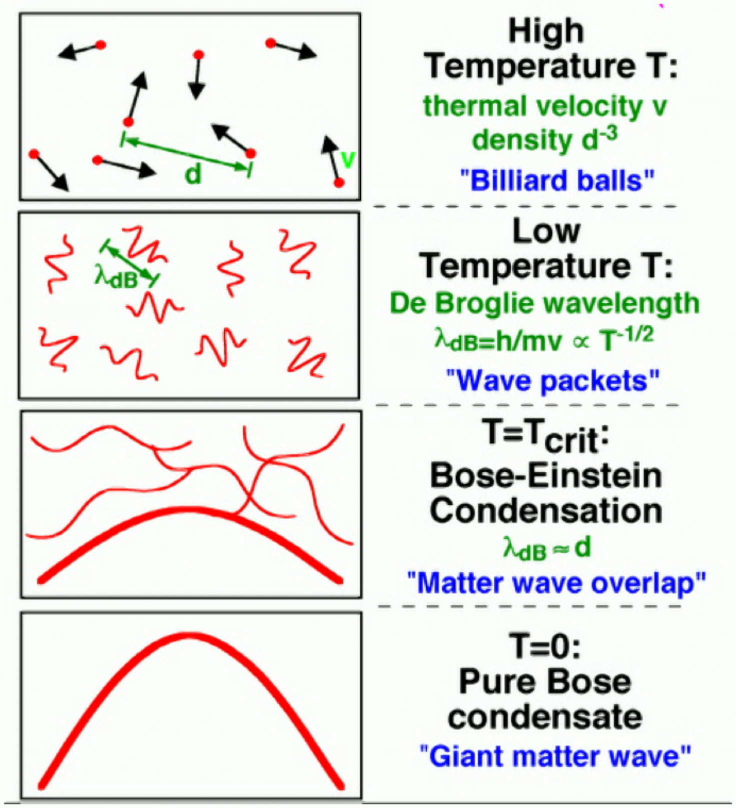
Very high principal quantum number $n \gg 5$,
these are HUGE atoms...

Johannes Rydberg



6

Bose-Einstein Condensates



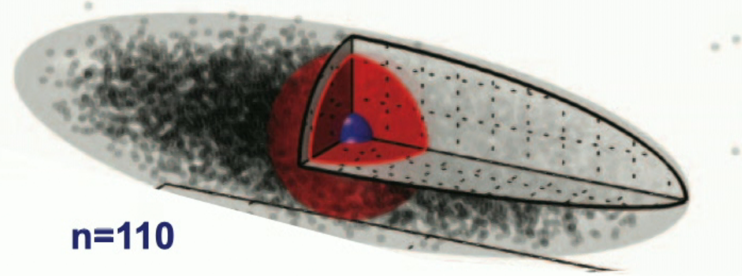
from: Durfee and Ketterle
Opt. Express **2** (1998) 299.

$$\Psi(\mathbf{R}_1, \cdots, \mathbf{R}_N) \to \otimes_{k=1}^{N} \phi(\mathbf{R}_k)$$

$$\hat{\Psi}(\mathbf{R}) \to \langle \hat{\Psi}(\mathbf{R}) \rangle = \phi(\mathbf{R})$$

Rydberg atoms in BEC

*Single large Rydberg atom in **BEC***



n=110

n=202

- Naturally excite Rydberg states in an ultracold gas or even BEC

- Extreme atoms in an extreme environment

J. Balewski *et al.*,
Nature **502** (2013) 664.

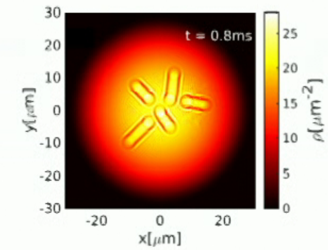
also:
Celistrino-Teixeira *et al.*,
Phys. Rev. Lett. **115** (2015) 013001.
F. Carmargo *et al.*,
Phys. Rev. Lett. **120** (2018) 083401.
M. Mizoguchi *et al.*,
Phys. Rev. Lett. **124** (2020) 253201.

Outline

(I) Phase imprinting by Rydberg atoms

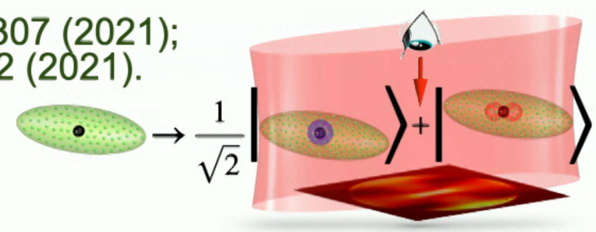
S. Tiwari and S. Wüster,
PRA **99** 043616 (2019)

S. Tiwari *et al.* NJP **24** 073005 (2022)



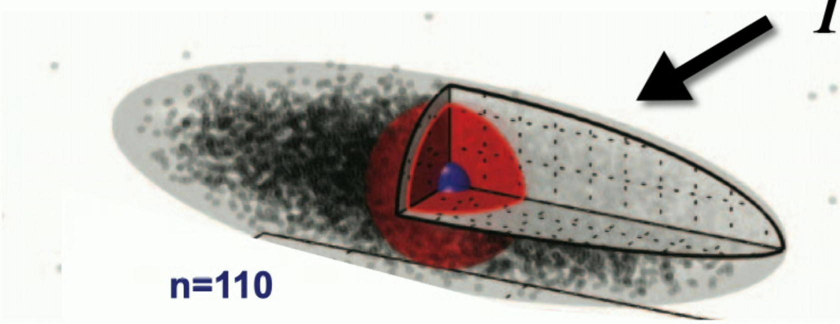
(II) Decoherence of Rydberg qubits in a BEC

S. Rammohan *et al.* PRA **103**, 063307 (2021);
Phys. Rev. A (Letters) **104**, L060202 (2021).



Rydbergs in BEC

$T \sim$ **nK**

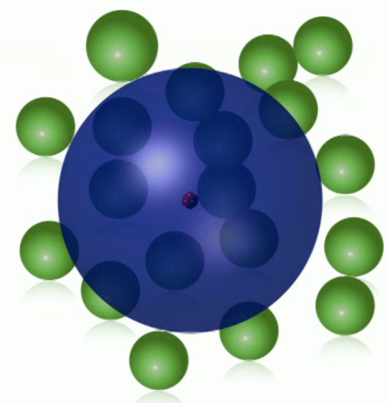


n=110

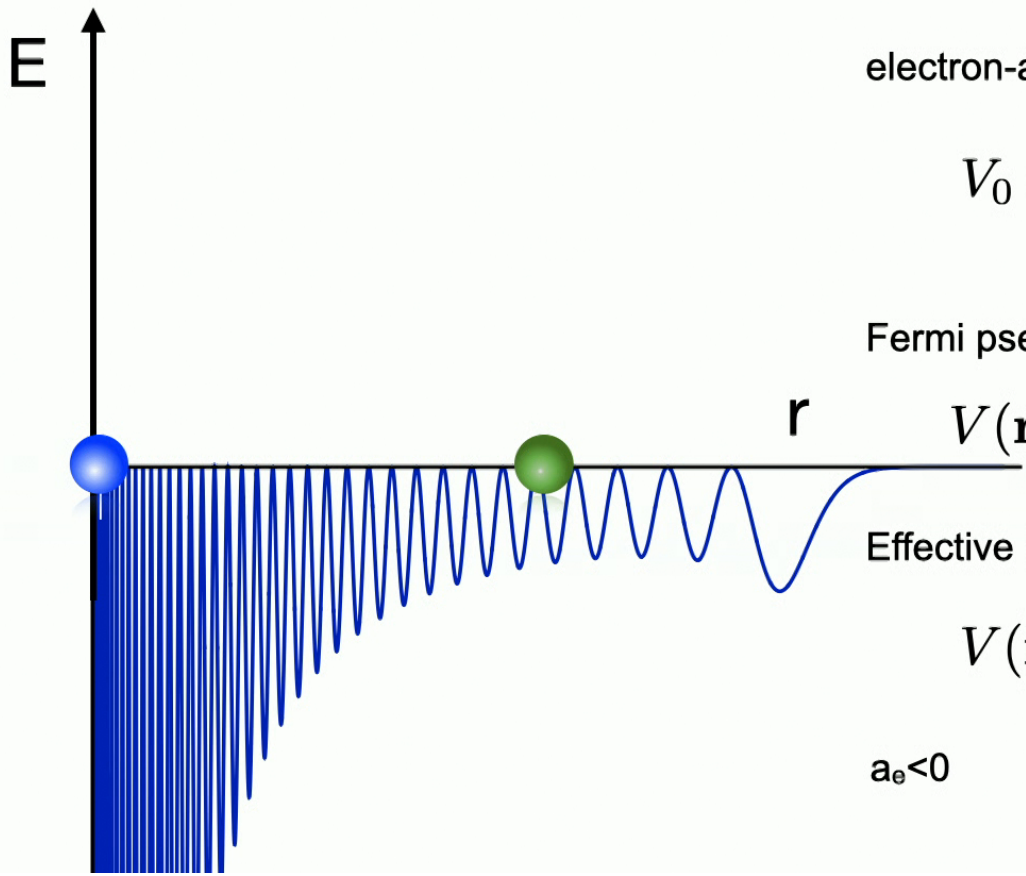
n=202

J. Balewski *et al.*,
Nature **502** (2013) 664.

100 - 1000 GS atoms **within** Rydberg orbit!!



Interactions with ground-state atoms



electron-atom s-wave scattering

$$V_0 = \frac{2\pi\hbar^2 a_e}{m_e}$$

Fermi pseudo potential

$$V(\mathbf{r}) = V_0 \delta(\mathbf{x}_e - \mathbf{r})$$

Effective Rydberg-GS potential

$$V(\mathbf{r}) = V_0 |\Psi_e(\mathbf{r})|^2$$

$a_e < 0$

Phase imprinting

GPE

$$i\hbar\frac{\partial}{\partial t}\phi(\mathbf{R}) = \left(-\frac{\hbar^2}{2m}\nabla^2 + g\,|\,\phi(\mathbf{R})\,|^2 + V_0\,|\,\psi(\mathbf{R}-\mathbf{x}_{imp})\,|^2\right)\phi(\mathbf{R})$$

Phase imprinting: $\phi(\mathbf{R},t) = \phi(\mathbf{R},0)\; e^{-iV_0|\psi(\mathbf{R}-\mathbf{x}_{imp})|^2 t/\hbar}$

see e.g.
Dobrek et al. PRA **60** (1999) R3381,
R. Mukherjee et al. PRL **115** (2015) 040401.

Phase imprinting

GPE

$$i\hbar\frac{\partial}{\partial t}\phi(\mathbf{R}) = \left(-\frac{\hbar^2}{2m}\nabla^2 + g\,|\phi(\mathbf{R})|^2 + V_0\,|\psi(\mathbf{R}-\mathbf{x}_{imp})|^2\right)\phi(\mathbf{R})$$

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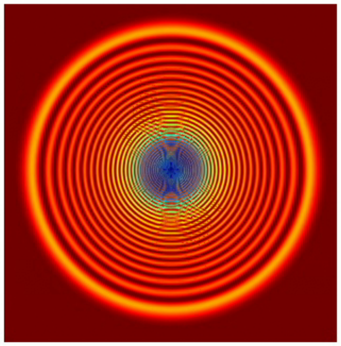
R. Mukherjee et al. PRL **115** (2015) 040401.

$|0\rangle \rightarrow |ns\rangle$

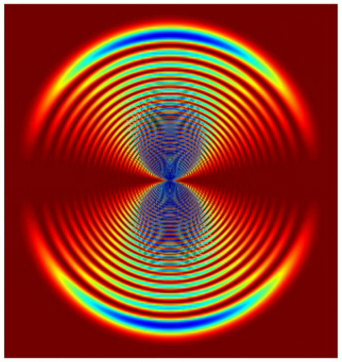


see also: Karpiuk et al. NJP **17** (2015) 053046

state-dependent Imprinted phase pattern

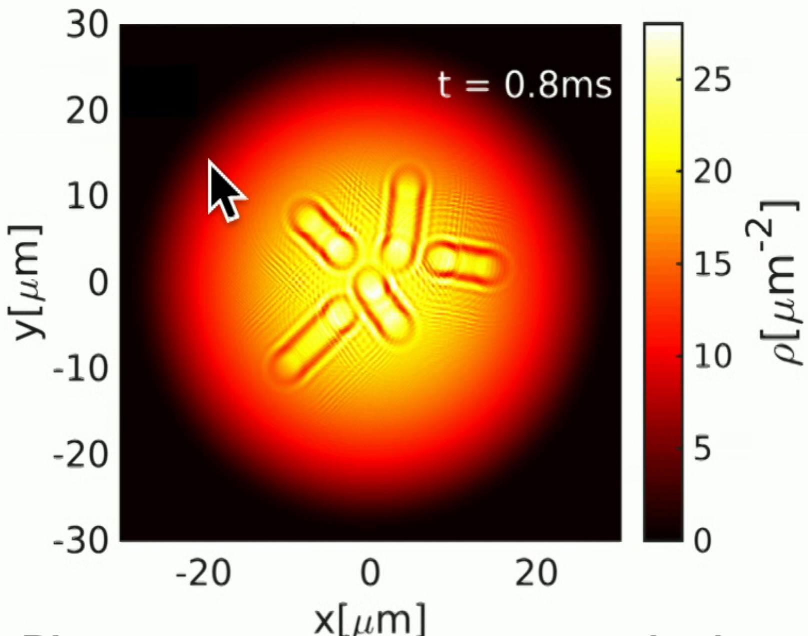
Density perturbation weak

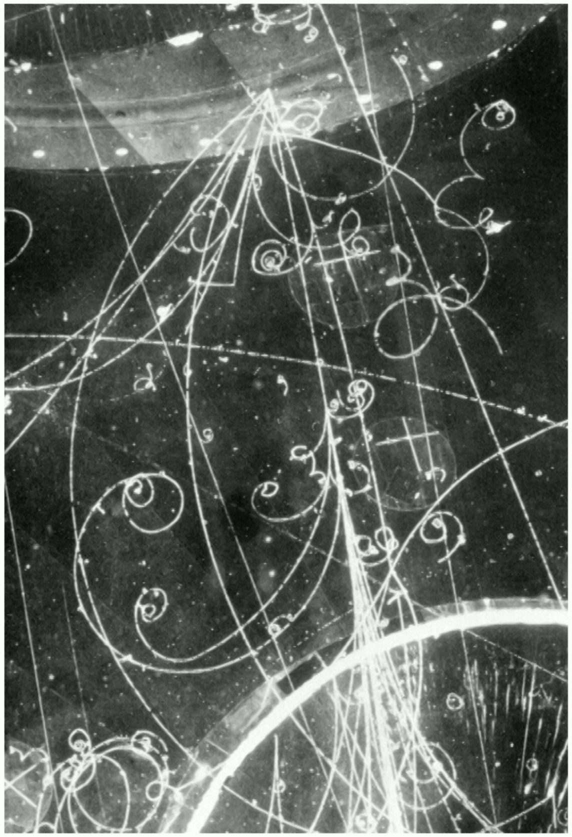
$|1\rangle \rightarrow |np\rangle$



Rydberg "Bubble chamber" (2D)

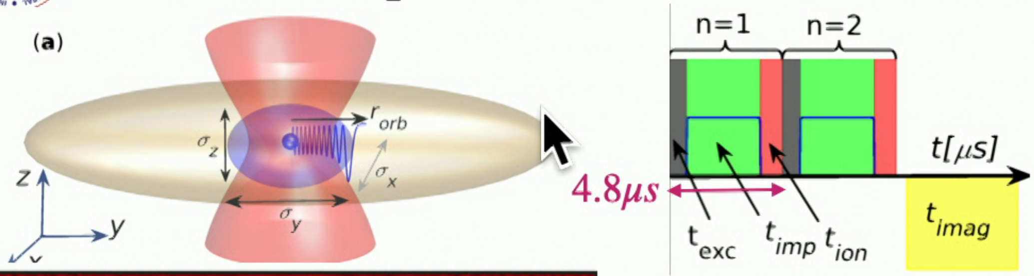
S. Tiwari and S. Wüster,
PRA **99** 043616 (2019)

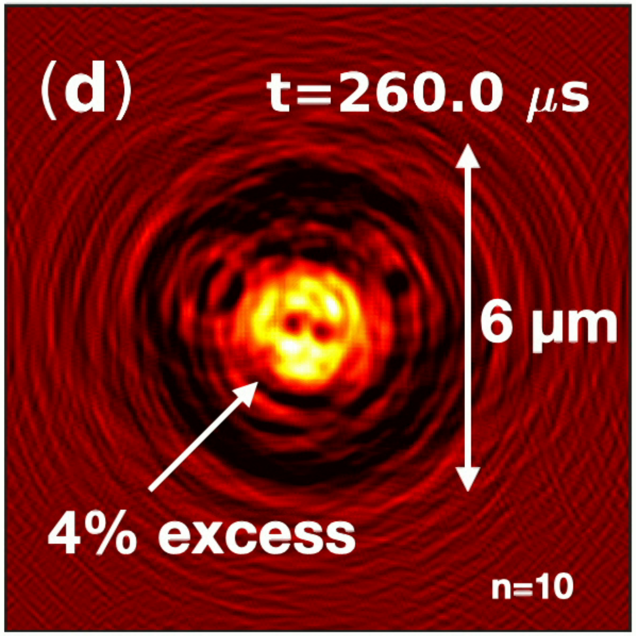




Phase imprint/ momentum kick
converts into density changes later

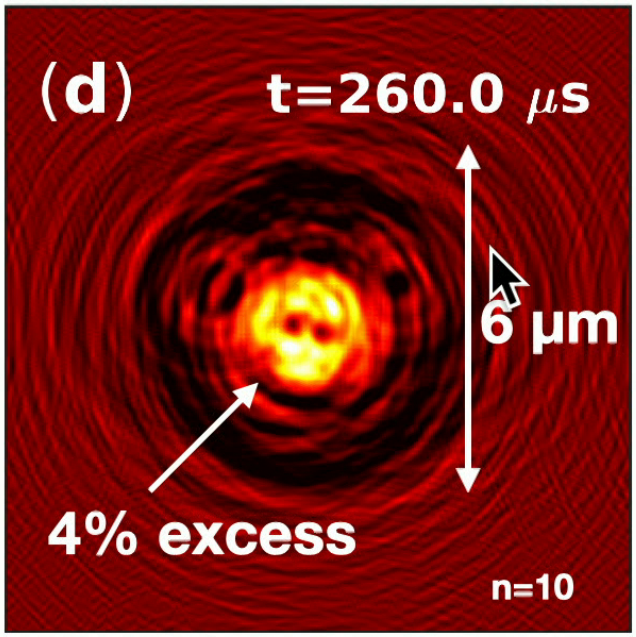
Repeated excitation





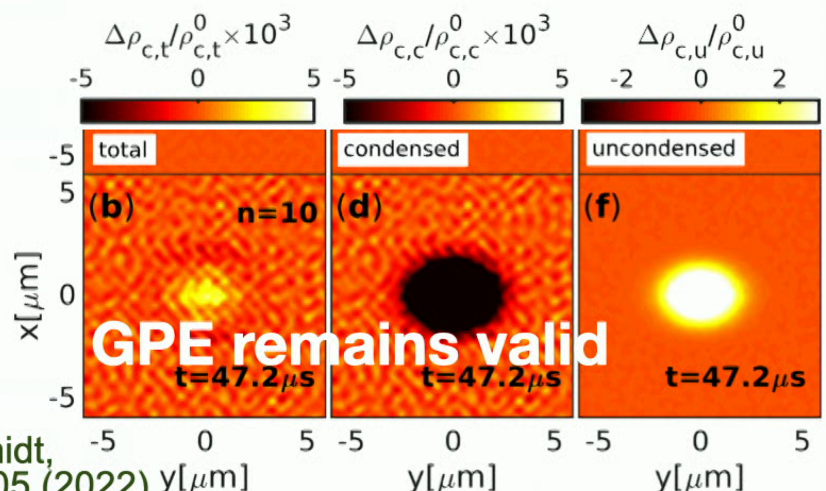
S. Tiwari, F. Engel, M. Wagner, R. Schmidt,
F. Meinert and S. Wüster NJP **24** 073005 (2022)

Repeated excitation



e.g. Blakie *et al.*, *(review)*
Advances in Physics **57** 363 (2008)

Truncated Wigner simulation



S. Tiwari, F. Engel, M. Wagner, R. Schmidt,
F. Meinert and S. Wüster NJP **24** 073005 (2022)

Outline

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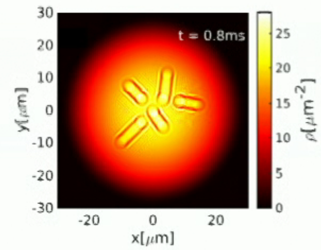

(II) Decoherence of Rydberg qubits in a BEC

S. Rammohan *et al.* PRA **103**, 063307 (2021);
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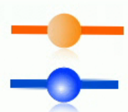
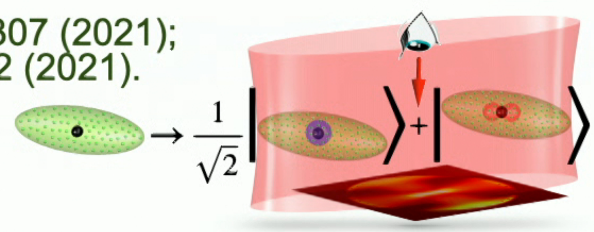
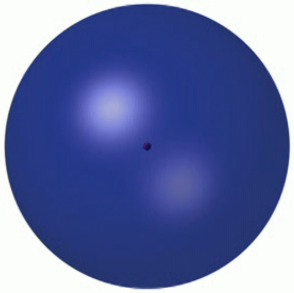




Rydberg qubit



$|ns\rangle$

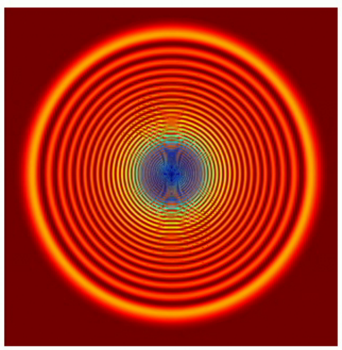
n=80, l=0

$|\downarrow\rangle$

$|np\rangle$

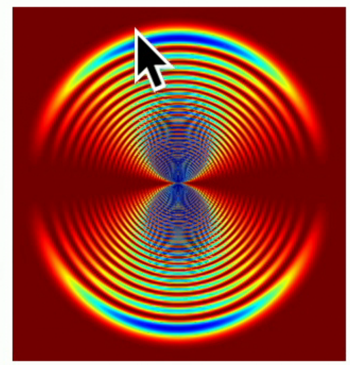
n=80, l=1

$|\uparrow\rangle$

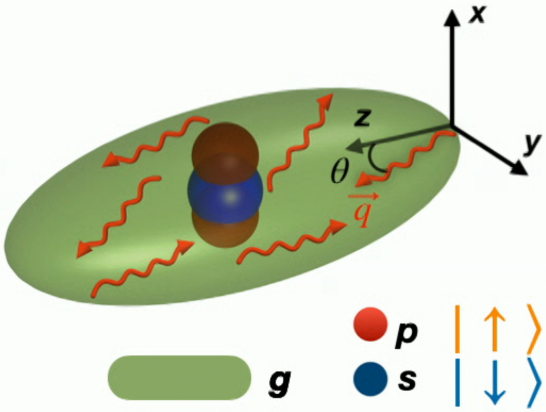


different
Imprinted
pattern

see also:
Karpiuk et al.
NJP **17** (2015) 053046



Bogoliubov Spin-Boson model



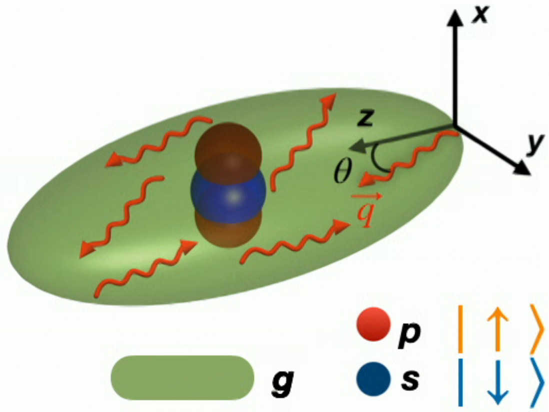
Many-body Hamiltonian

$$\hat{H} = \sum_k \int d^3\mathbf{x} \Big[\hat{\Psi}_k^\dagger(\mathbf{x}) \Big(-\frac{\hbar^2}{2m}\nabla^2 + E_k \Big) \hat{\Psi}_k(\mathbf{x}) \qquad (1)$$

$$+ \frac{1}{2} \sum_{i,j,s} \int d^3\mathbf{y} \hat{\Psi}_k^\dagger(\mathbf{x}) \hat{\Psi}_i^\dagger(\mathbf{y}) U_{kijs}(\mathbf{x}-\mathbf{y}) \hat{\Psi}_j(\mathbf{y}) \hat{\Psi}_s(\mathbf{x}) \Big].$$

see also: Middelkamp et al. PRA **76** (2007) 022507.

Bogoliubov Spin-Boson model



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$$+ \frac{1}{2} \sum_{i,j,s} \int d^3\mathbf{y} \hat{\Psi}_k^\dagger(\mathbf{x}) \hat{\Psi}_i^\dagger(\mathbf{y}) U_{kijs}(\mathbf{x}-\mathbf{y}) \hat{\Psi}_j(\mathbf{y}) \hat{\Psi}_s(\mathbf{x}) \Big].$$

see also: Middelkamp et al. PRA **76** (2007) 022507.

Bose gas beyond mean field (Bogoliubov)

$$\hat{\Psi}_g(\mathbf{x}) = \phi_0(\mathbf{x}) + \sum_{\mathbf{q}} \left(u_{\mathbf{q}}(\mathbf{x}) \hat{b}_{\mathbf{q}} - v^*_{\mathbf{q}}(\mathbf{x}) \hat{b}^\dagger_{\mathbf{q}} \right)$$

Spin-Boson Hamiltonian

$$\hat{\sigma}_z = |p\rangle\langle p| - |s\rangle\langle s|$$

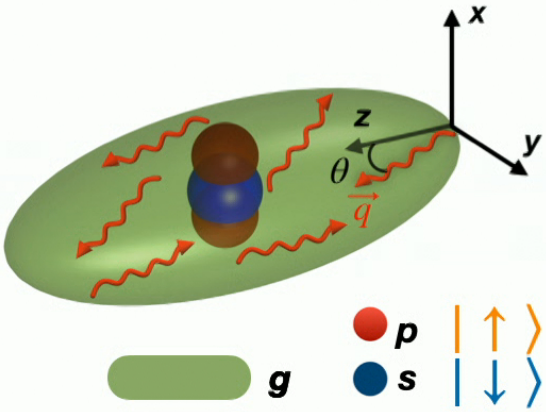
$$\hat{H}_{syst} = \frac{\Delta E(t)}{2} \hat{\sigma}_z \qquad \hat{H}_{\mathrm{env}} = \sum_{\mathbf{q}} \hbar\omega_{\mathbf{q}} \tilde{b}^\dagger_{\mathbf{q}} \tilde{b}_{\mathbf{q}}$$

$$\hat{H}_{\mathrm{int}} = \sum_{\mathbf{q}} \frac{\Delta\kappa_{\mathbf{q}}}{2} \left(\tilde{b}_{\mathbf{q}} + \tilde{b}^\dagger_{\mathbf{q}} \right) \hat{\sigma}_z. \quad +$$

S. Rammohan *et al.* PRA **103**, 063307 (2021)

For g-impurities:
Jaksch group and Lewenstein group

Open quantum system



Spin-Boson Hamiltonian

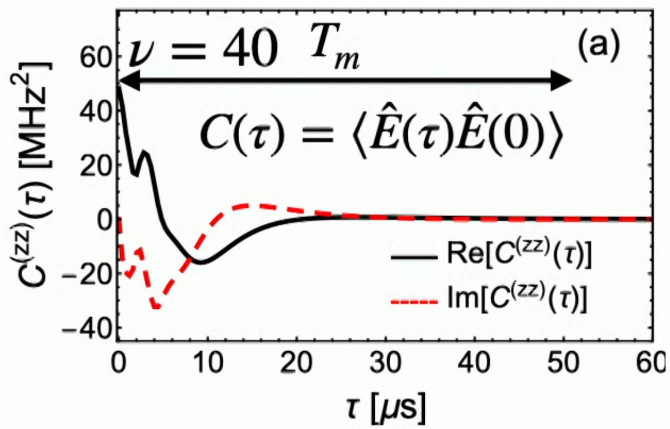
$$\hat{H}_{\rm syst} = \frac{\Omega_{\rm mw}}{2}\hat{\sigma}_x + \frac{\Delta E(t)}{2}\hat{\sigma}_z, \quad \hat{H}_{\rm env} = \sum_{\mathbf{q}} \hbar\omega_{\mathbf{q}}\, \tilde{b}^\dagger_{\mathbf{q}}\tilde{b}_{\mathbf{q}}$$

S E

$$\hat{H}_{\rm int} = \sum_{\mathbf{q}} \frac{\Delta\kappa_{\mathbf{q}}}{2}\left(\tilde{b}_{\mathbf{q}} + \tilde{b}^\dagger_{\mathbf{q}}\right)\hat{\sigma}_z.$$

E S +

$$\hat{H}_{int} = \hat{E} \otimes \hat{S}$$



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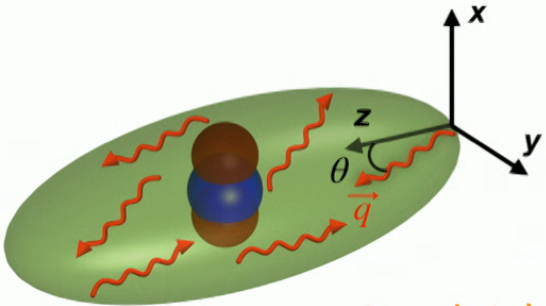
Open quantum system



Spin-Boson Hamiltonian

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S E

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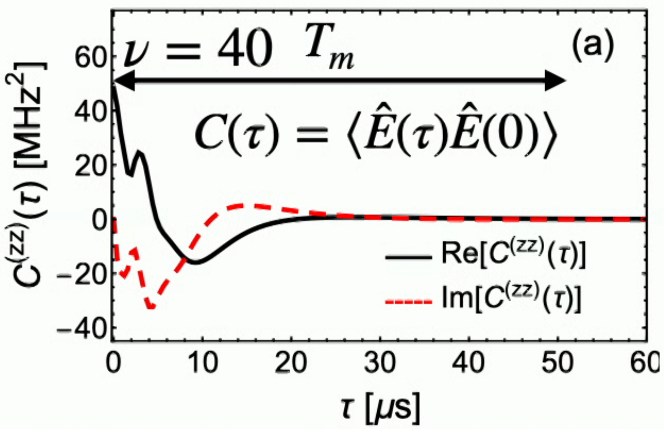
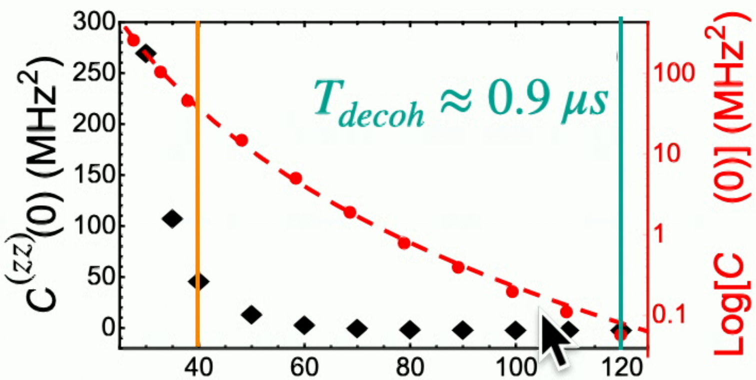
E S +

g p $|\uparrow\rangle$ s $|\downarrow\rangle$

$$\hat{H}_{int} = \hat{E} \otimes \hat{S}$$

$$T_{decoh} \approx 1/\sqrt{2C(0)}$$





$T_{decoh} \approx 20\ ns$ ν

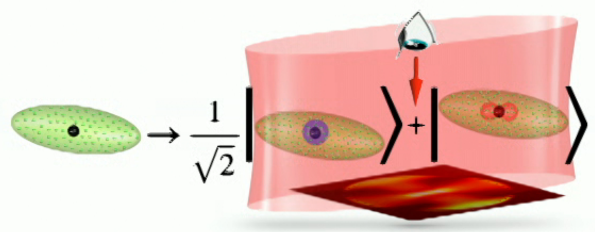
S. Rammohan *et al.* PRA **103**, 063307 (2021)

“Image” decohering state

Rydberg state entangled with BEC

$$|\,\Psi_{\rm tot}(t)\,\rangle = \frac{1}{\sqrt{2}}|\uparrow\rangle \otimes |\,\Psi_\uparrow(t)\,\rangle + \frac{1}{\sqrt{2}}|\downarrow\rangle \otimes |\,\Psi_\downarrow(t)\,\rangle$$

Image environmental part of entangled state?

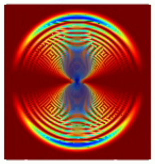


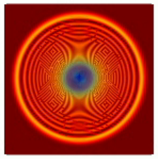
Rabi π/2 Micr

$$|\Psi_{\rm tot}\rangle = \frac{1}{2} \quad \ldots \quad \rangle + i|\Psi_\downarrow\rangle)]$$

Measurement of Rydberg state, selection of $|\uparrow\rangle$

$$|\Psi_{\rm ms}(t)\rangle \sim A[|\Psi_\uparrow(t)\rangle - i|\Psi_\downarrow(t)\rangle]$$

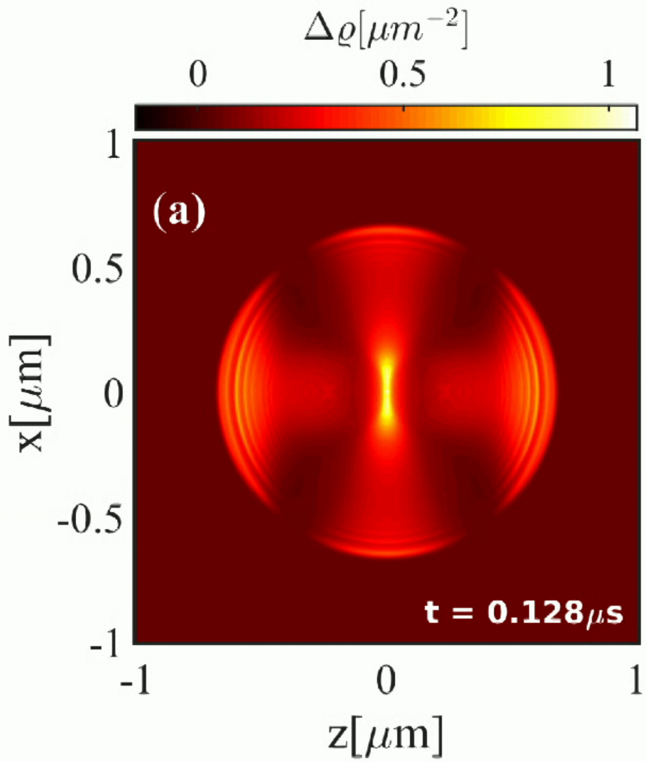


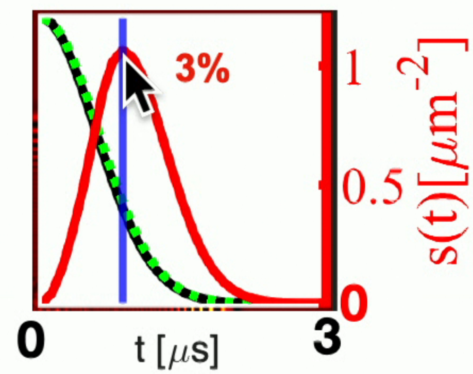


Imaging decohering environment

BEC column densities in

$|\Psi_{ms}(t)\rangle \sim A[|\Psi_\uparrow(t)\rangle - i|\Psi_\downarrow(t)\rangle]$ **(minus)** $\hat{\rho} = (|\Psi_\uparrow\rangle\langle\Psi_\uparrow| + |\Psi_\downarrow\rangle\langle\Psi_\downarrow|)/2$





- Transient glimpse at many-body entanglement at the root of decoherence:

$|\Psi_{tot}(t)\rangle = c_\uparrow|\uparrow\rangle \otimes |\Psi_\uparrow(t)\rangle + c_\downarrow|\downarrow\rangle \otimes |\Psi_\downarrow(t)\rangle$

S. Rammohan *et al.*
Phys. Rev. A (Letters) **104**, L060202 (2021).

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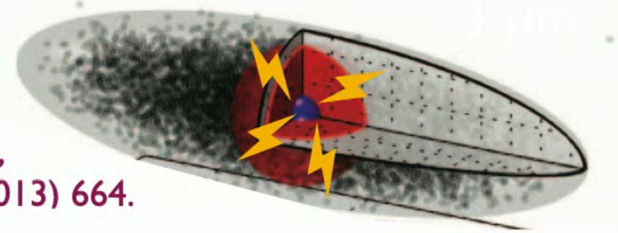
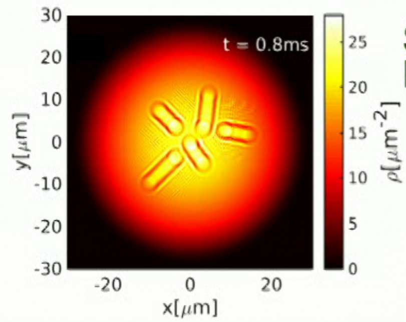
Summary

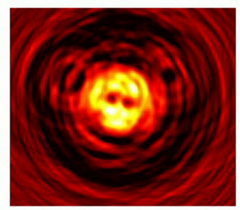
- Combination of two extreme systems: Rydberg atoms and BEC:
  J. Balewski *et al.*, Nature **502** (2013) 664.



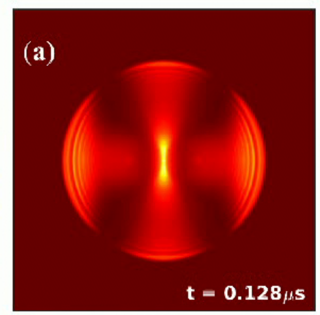
- Rydberg bubble chambers



S. Tiwari *et al.* PRA **99** 043616 (2019);



- Attractive BEC response
  S. Tiwari *et al.* NJP **24** 073005 (2022)



- Imaging the decohering interface
  S. Rammohan *et al.* PRA **103**, 063307 (2021); PRA (Letters) **104**, L060202 (2021)

Thanks for your attention