Rydberg atoms in Bose-Einstein condensed environments

from bubble chambers to controllable open quantum systems

Sebastian Wüster

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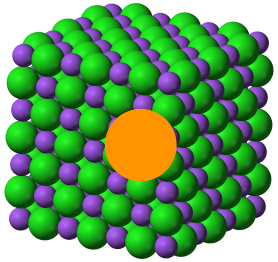
Indian Institute of Science Education and Research Bhopal, India

MPG-Partnergroup with:

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

(Quantum) impurities

regular bulk structure



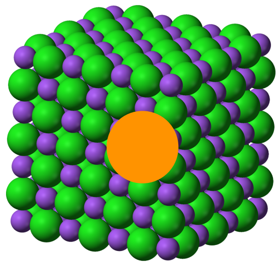
minority impurity

qualitatively new features

- Kondo effect
- Doping
- Polarons

(Quantum) impurities

regular bulk structure



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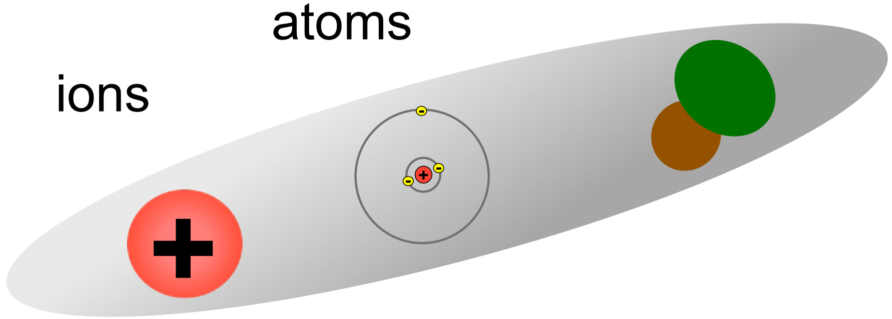
molecules

atoms

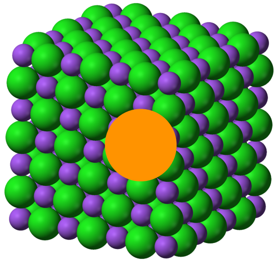
ions



ultra cold gas
or BEC

(Quantum) impurities

regular bulk structure



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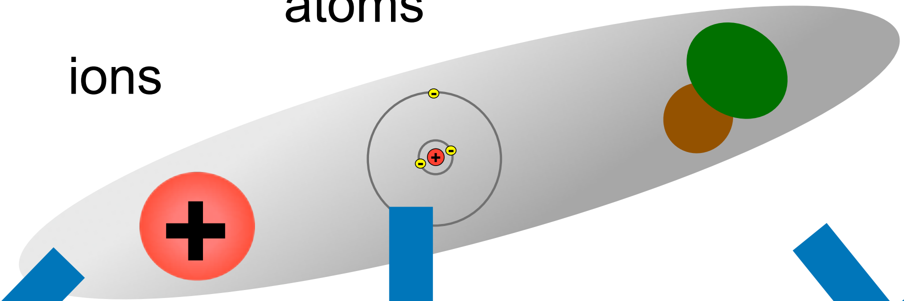

ultra cold gas
or BEC

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

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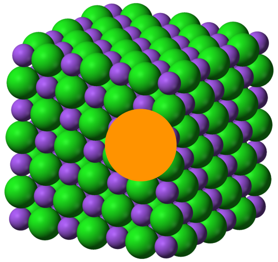

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Rydberg atoms

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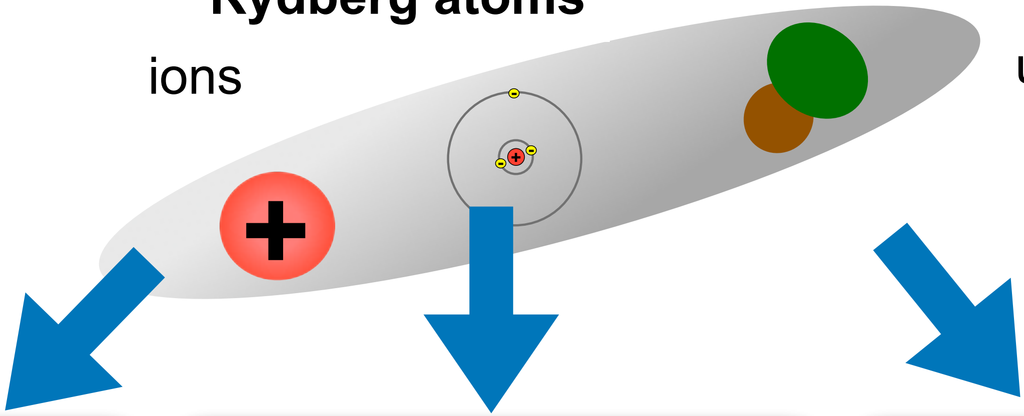

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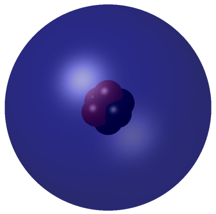
Rydberg atoms

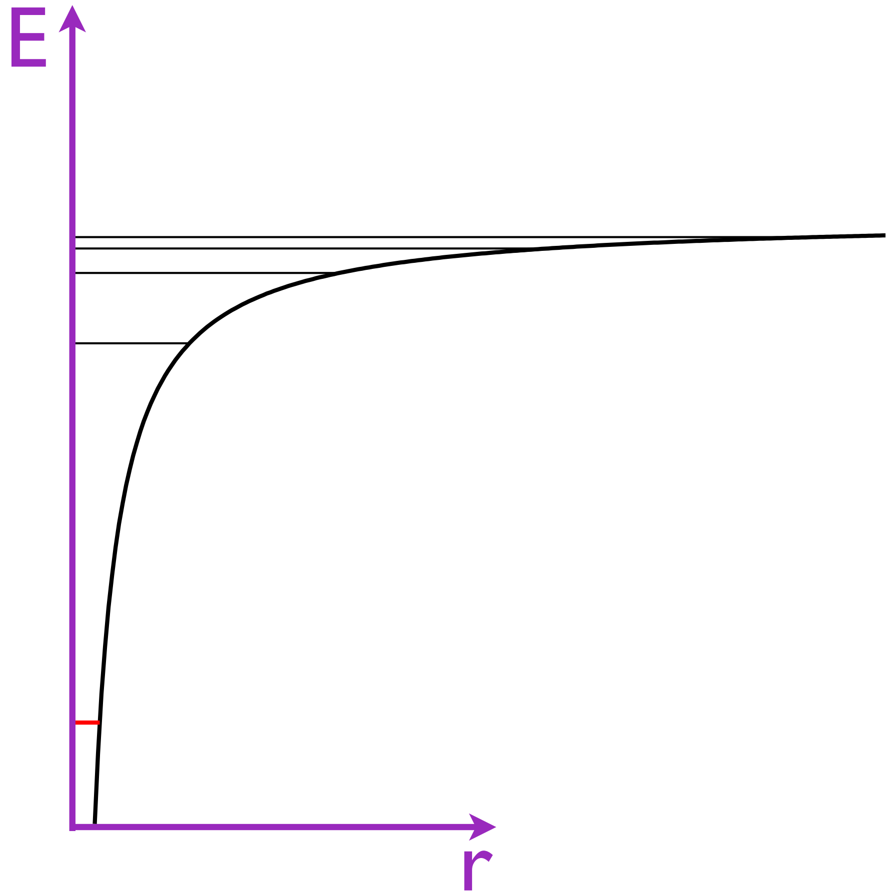
What are Rydberg atoms?

Electron quantum states (orbitals):

$$|\, nlm \,\rangle$$



n=1



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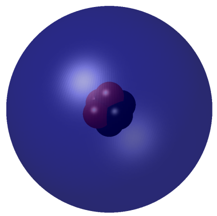
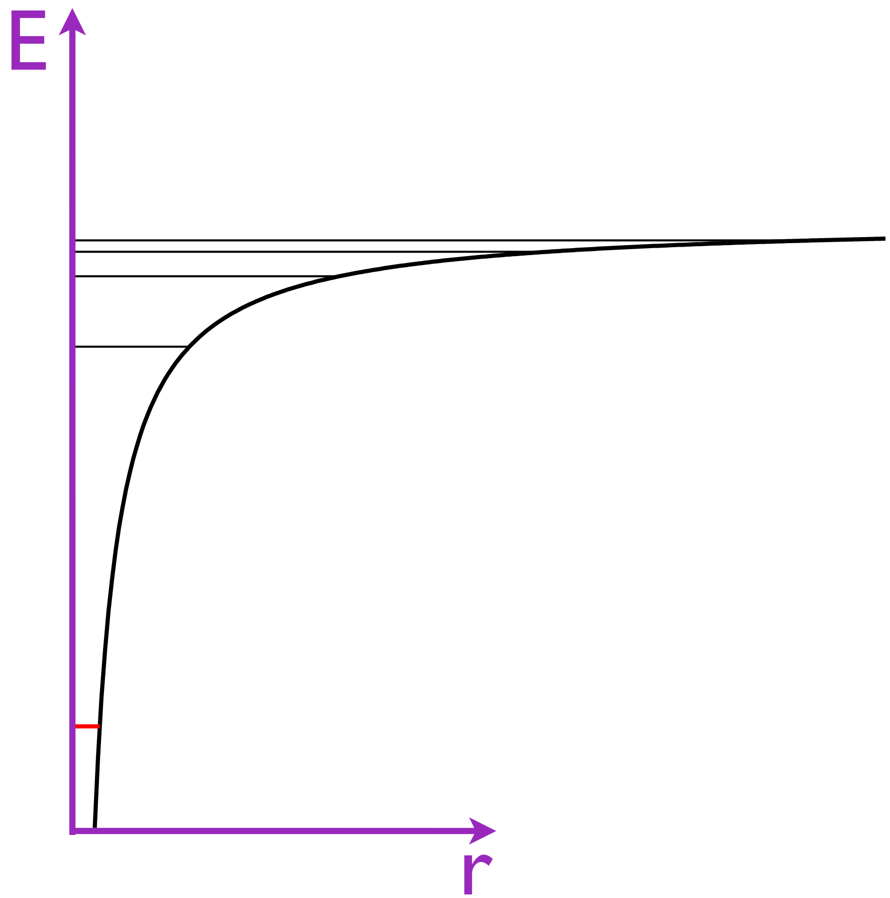


$\leftrightarrow$ 0.05 nm

n=1



Orbital radius: $r_{rad} \approx \frac{3}{2} a_0 n^2$

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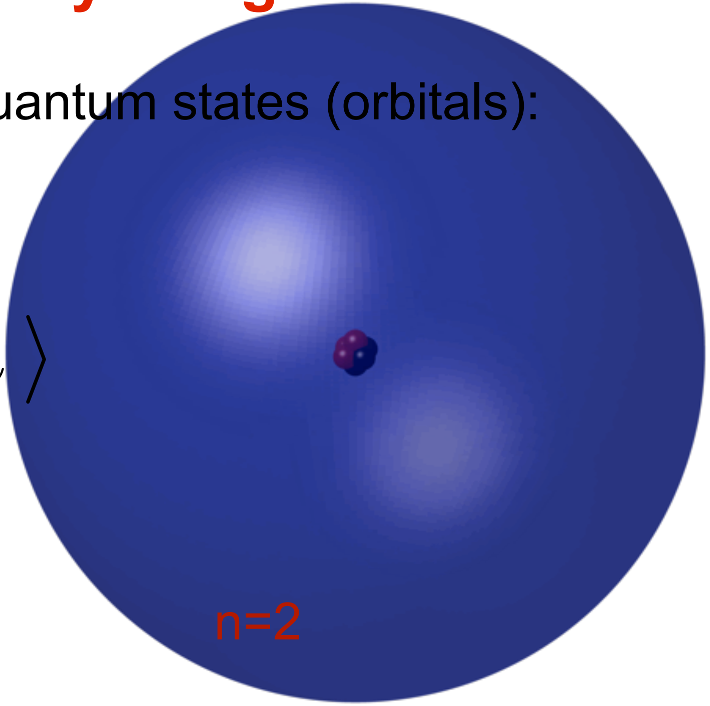

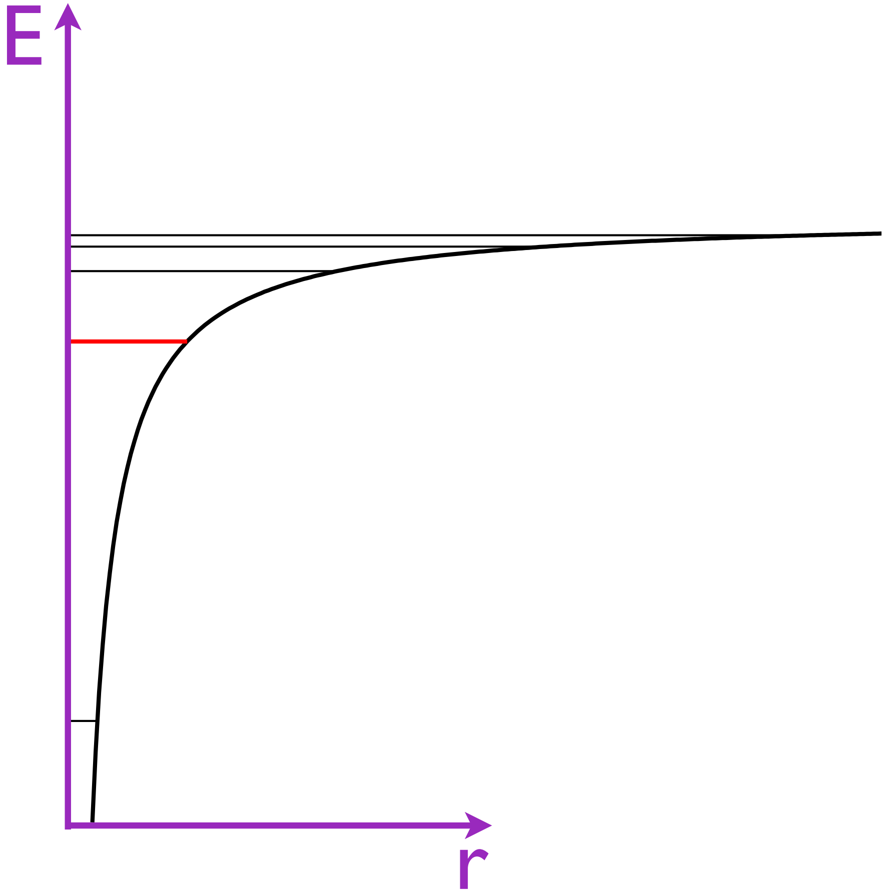

Orbital radius: $r_{\text{rad}} \sim n^2$

Rydberg atoms

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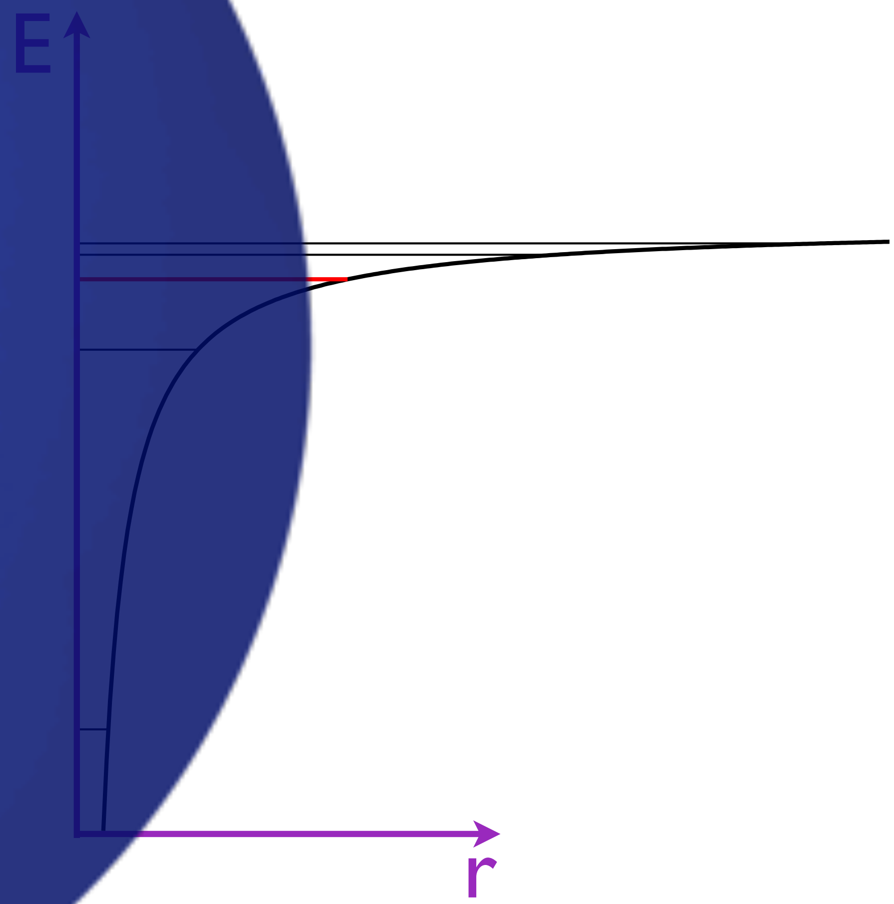
Electron quantum states (orbitals):

$$|\, nlm \,\rangle$$

n=3

Orbital radius: $r_{\text{rad}} \sim n^2$



Rydberg atoms

What are Rydberg atoms?

Johannes Rydberg

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

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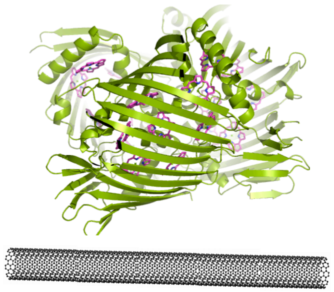
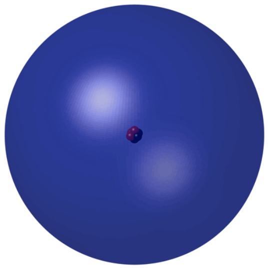




size of
nanotube/
biomolecule

20 nm

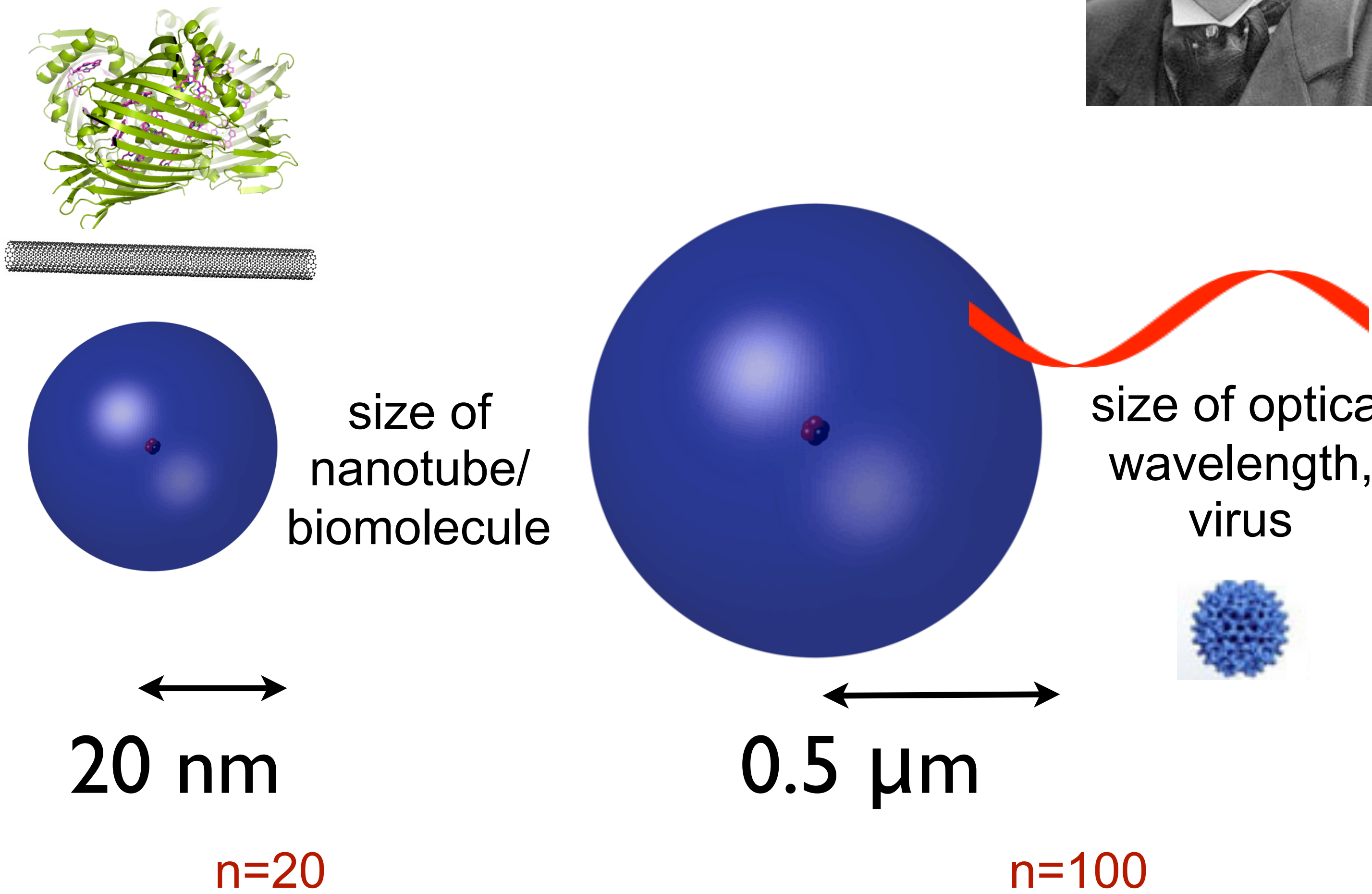
n=20

Rydberg atoms

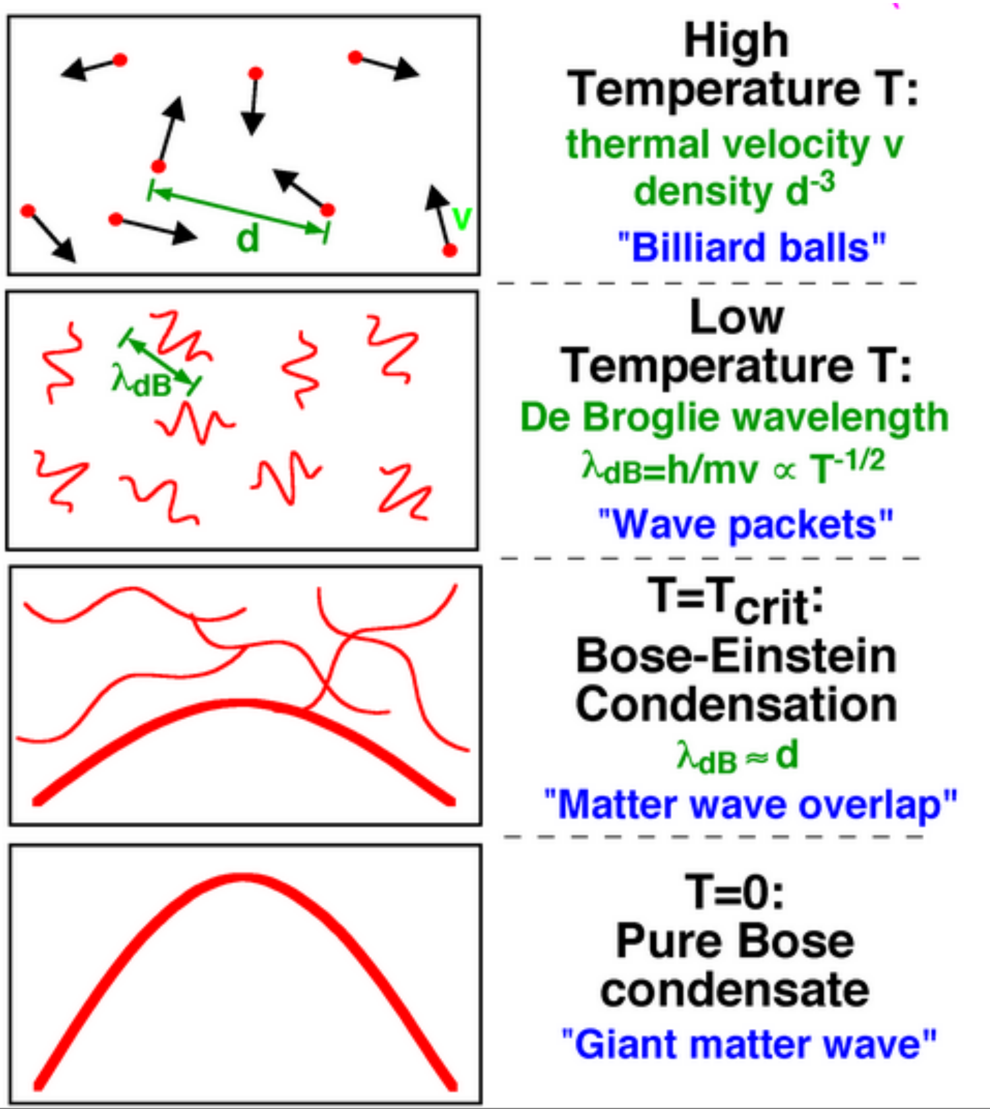
What are Rydberg atoms?

Very high principal quantum number n ≫ 5,
these are HUGE atoms...

Johannes Rydberg



Bose-Einstein Condensates



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

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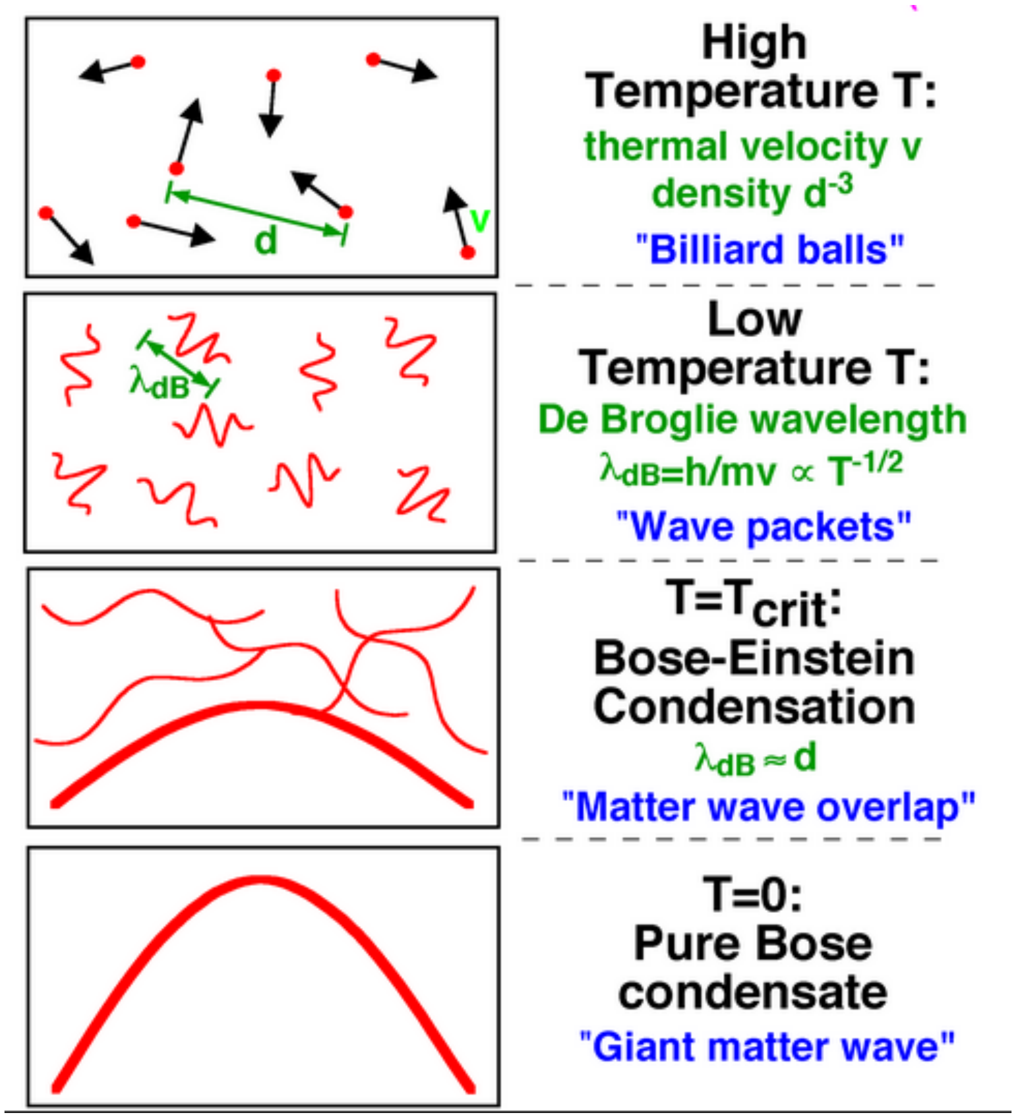

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$$\Psi(\mathbf{R}_1, \cdots, \mathbf{R}_N) \to \phi(\mathbf{R})$$

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

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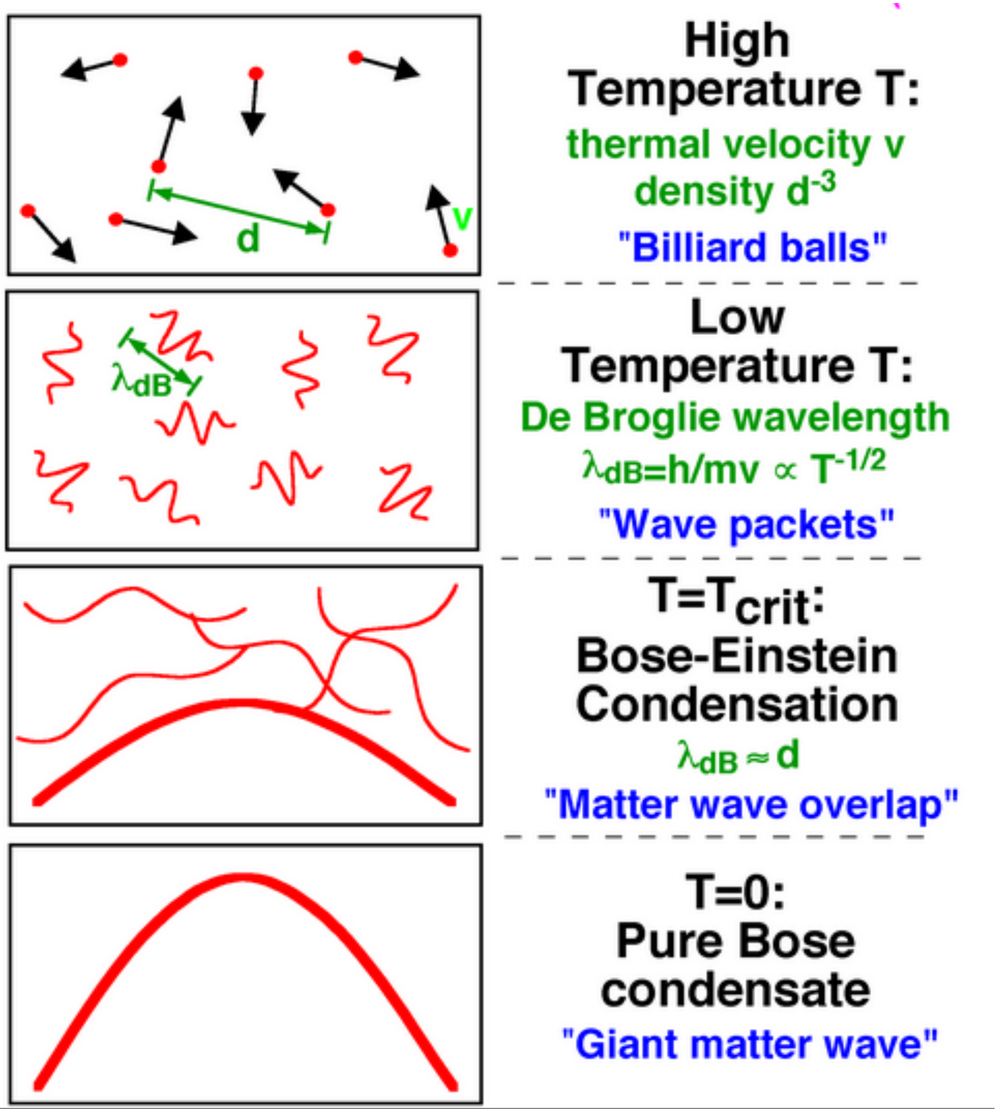

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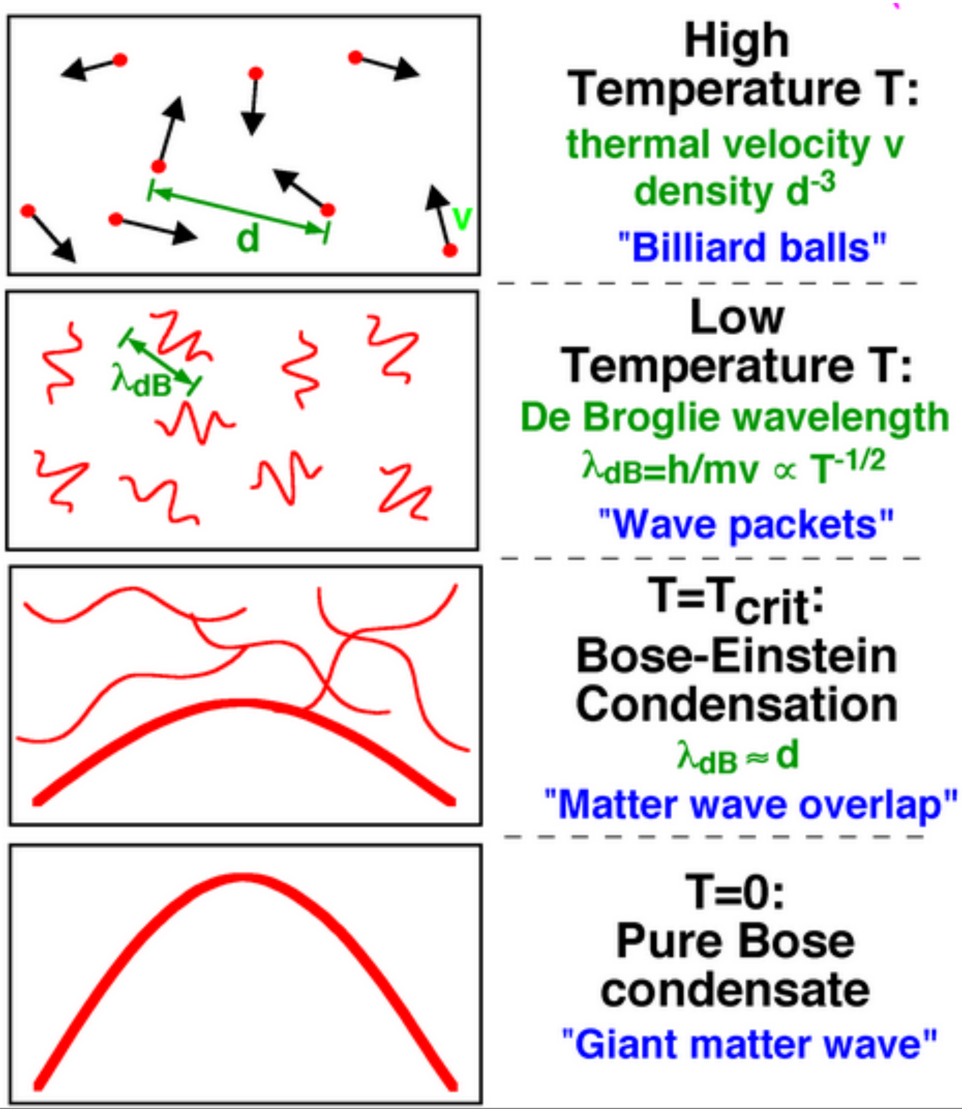
Gross Pitaevskii equation

$$i\hbar \frac{\partial}{\partial t}\phi(\mathbf{R}) = \left(-\frac{\hbar^2}{2m}\nabla^2 + W(\mathbf{R}) + U_0 |\phi(\mathbf{R})|^2 \right)\phi(\mathbf{R})$$

Bose-Einstein Condensates



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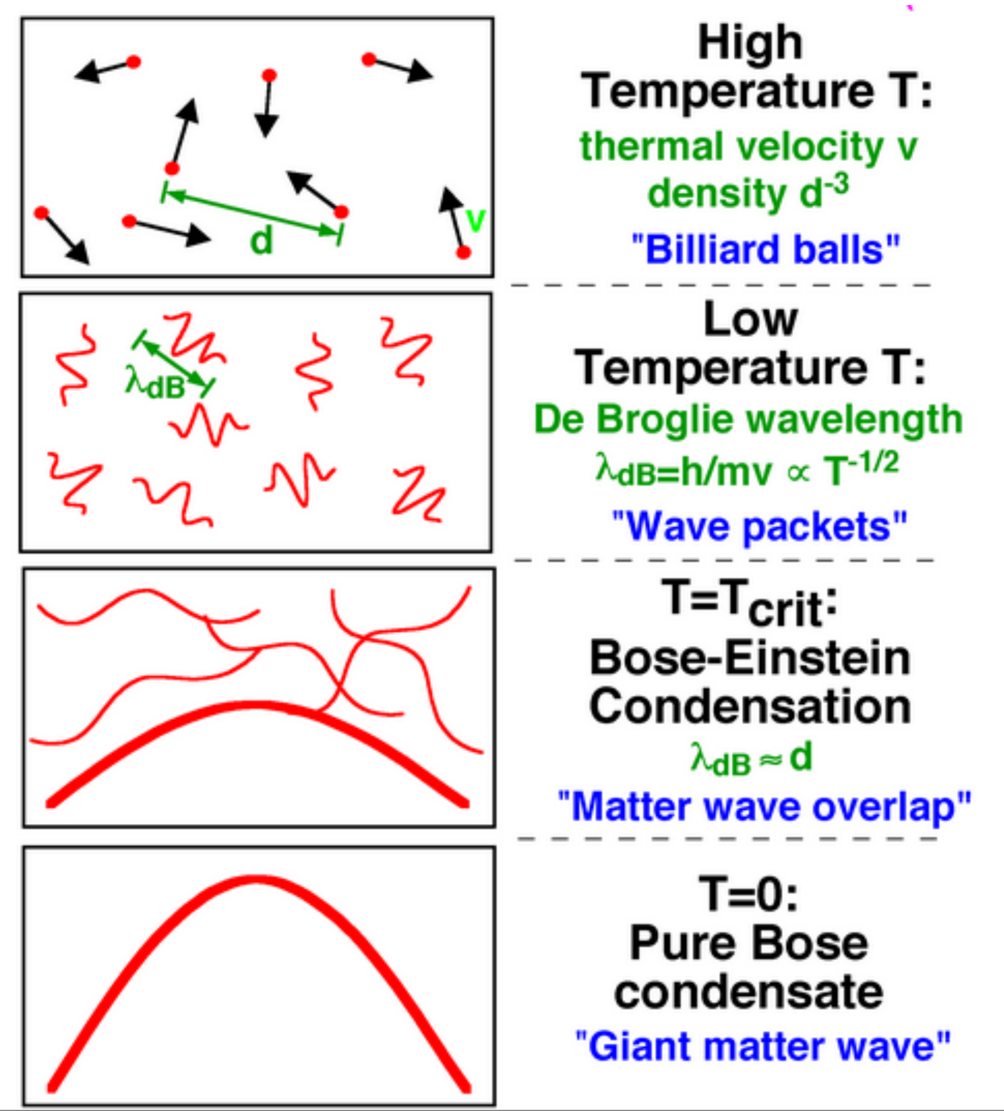
BEC density

Bose-Einstein Condensates



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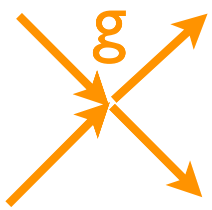
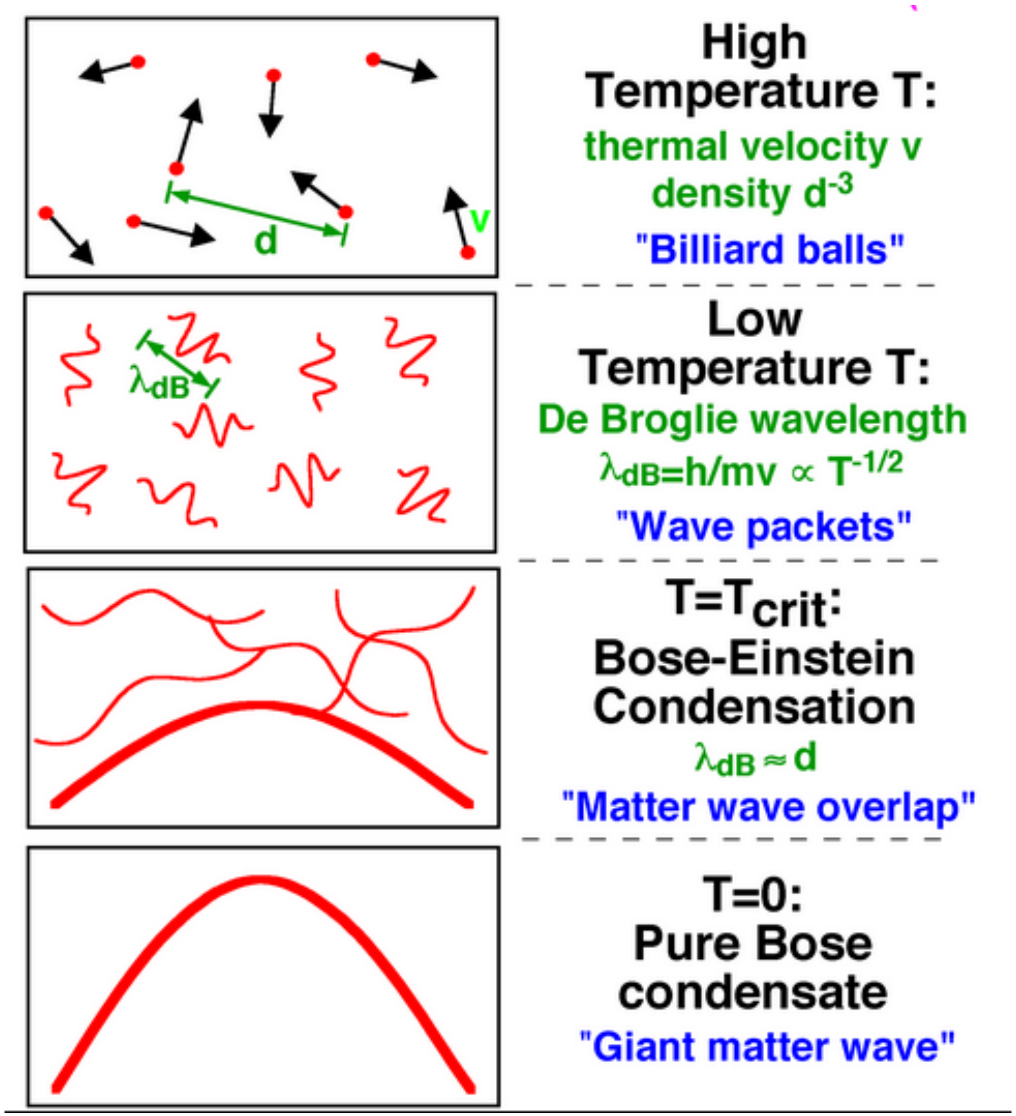


s-wave scattering

Bose-Einstein Condensates



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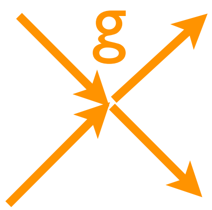


s-wave scattering

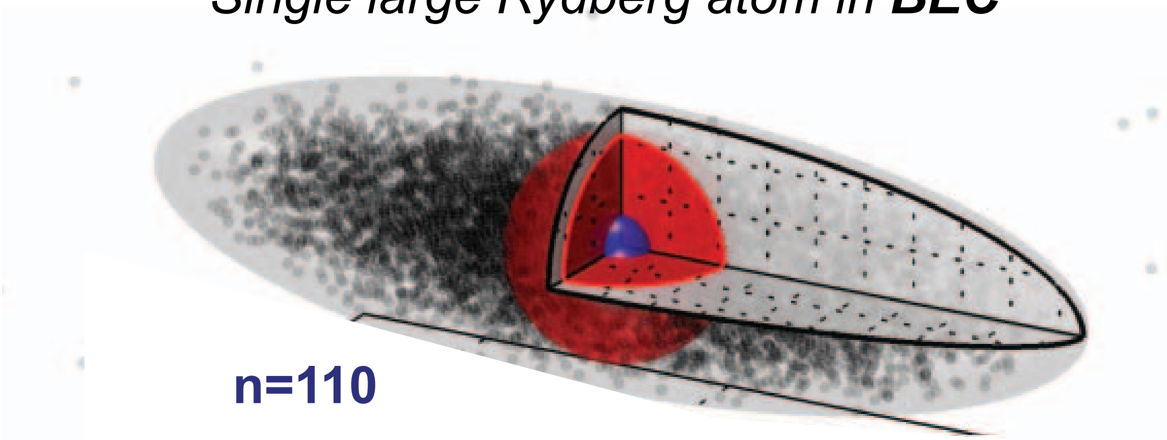
3D wavefunction (not 3^N D)

Phase coherence

$$\phi(\mathbf{R}) \in \mathbb{C}$$

Rydberg atoms in BEC

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



n=110

n=202

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

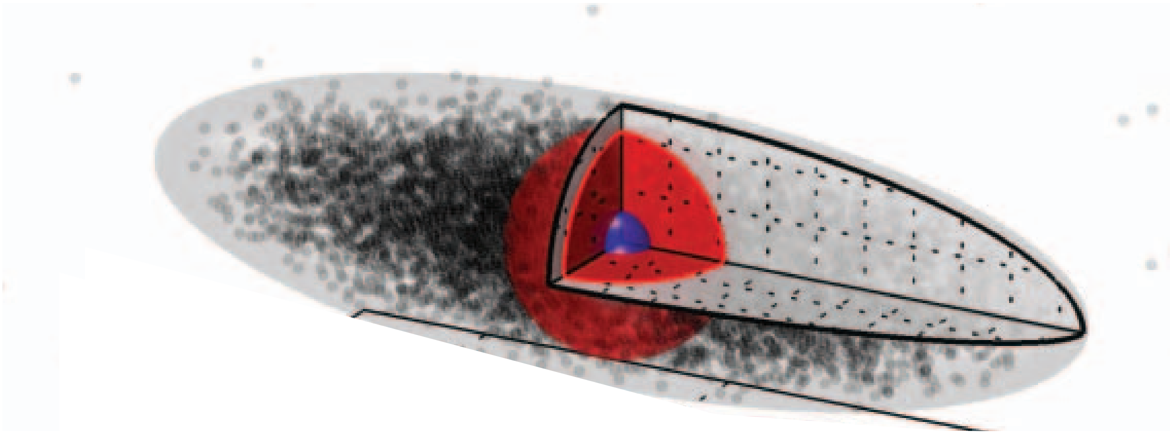
- Naturally excite Rydberg states in an ultracold gas or even BEC

- Extreme atoms in an extreme environment

also:
Celistrino-Teixeira *et al.*,
Phys. Rev. Lett. **115** (2015) 013001.

F. Carmargo *et al.*,
Phys. Rev. Lett. **120** (2018) 083401.

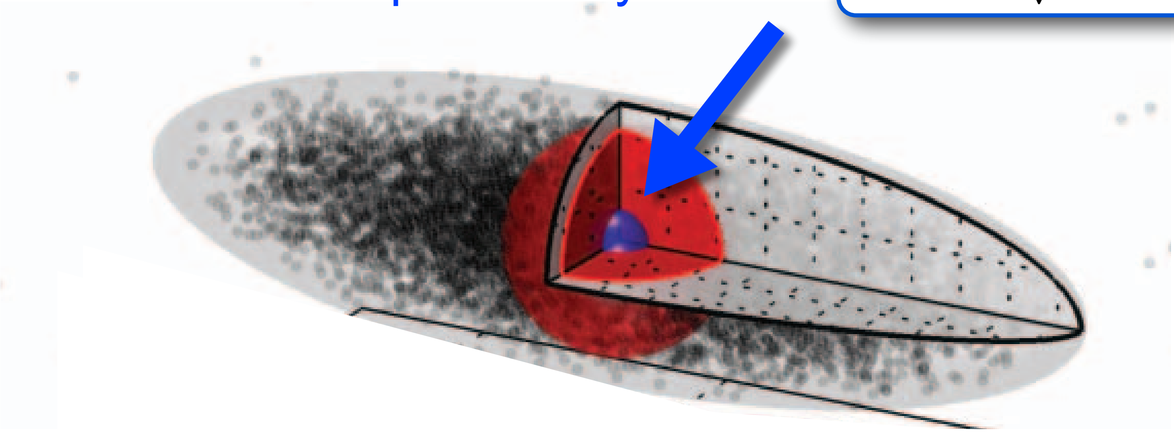
Rydberg-BEC interactions



Rydberg-BEC interactions

Well controlled simple quantum system

$$|\Psi\rangle = \frac{1}{\sqrt{2}}\left(|n=55,s\rangle + |n=55,p\rangle\right)$$



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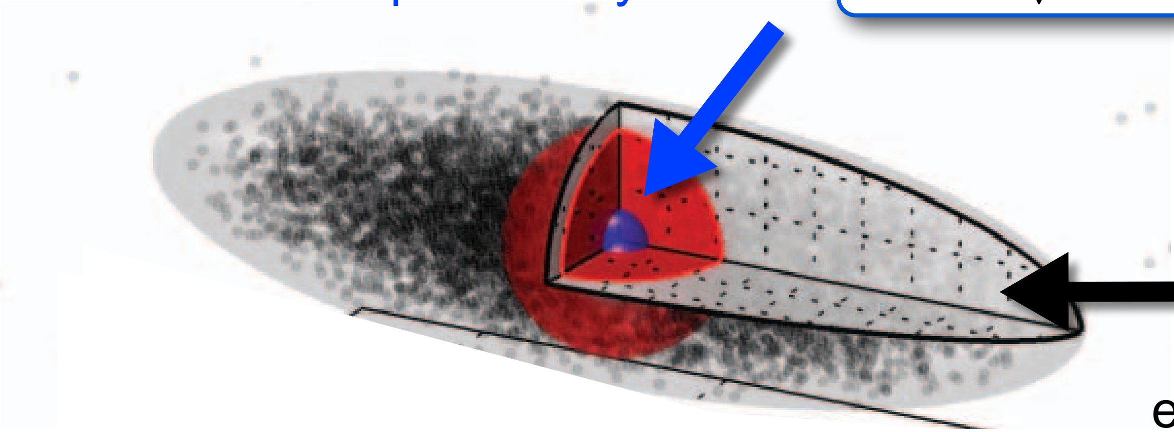

Well controlled environment

Bose Einstein condensate: mean field and phonons

$$\hat{\Psi}(x)$$

$$= \phi(x) + \sum_q (u_q(x)\hat{\alpha}_q - v_q^*(x)\hat{\alpha}_q^\dagger)$$

Rydberg-BEC interactions

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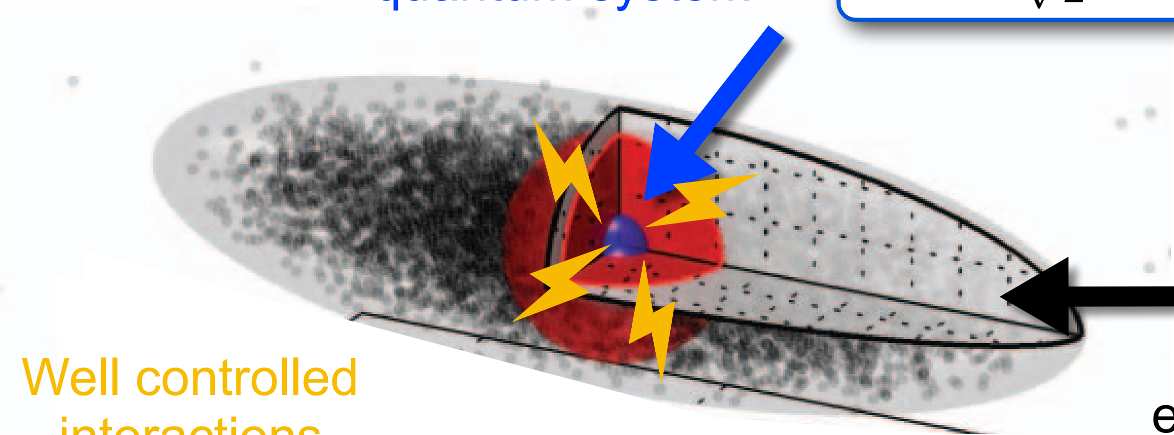
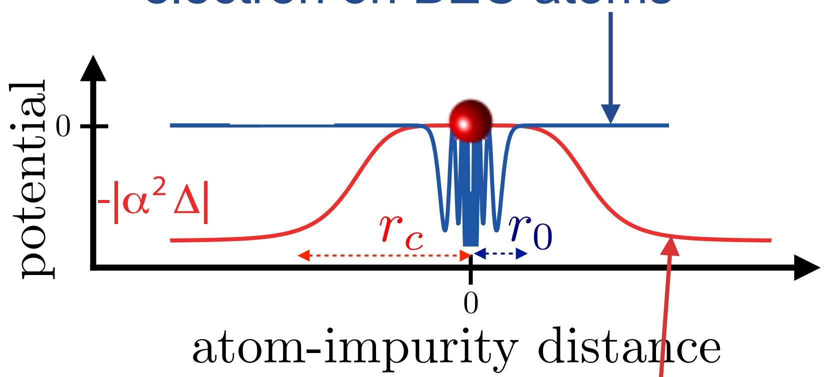


Well controlled environment

Well controlled interactions

Elastic scattering of Rydberg electron on BEC atoms



and/or: laser tunable dressed interactions

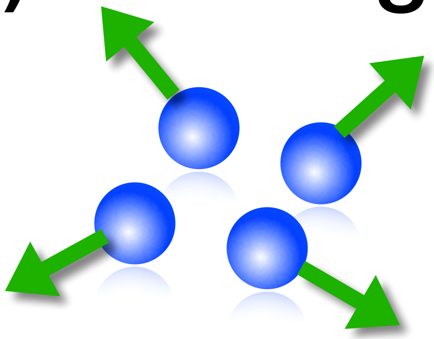
Bose Einstein condensate: mean field and phonons

$$\hat{\Psi}(x) = \phi(x) + \sum_q (u_q(x)\hat{\alpha}_q - v_q^*(x)\hat{\alpha}_q^\dagger)$$

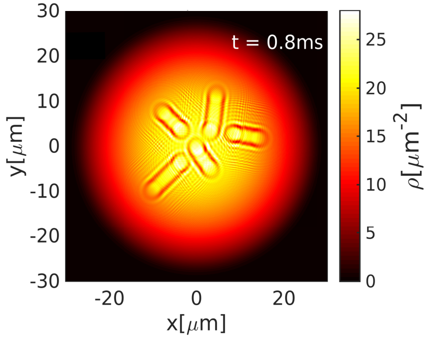
R. Mukherjee, C. Ates, Weibin Li and S. Wüster, PRL **115** 040401 (2015)

Outline

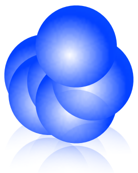
(I) Tracking of mobile Rydberg atoms in a BEC

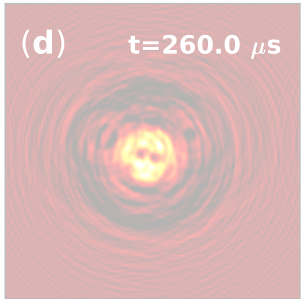


S. Tiwari and S. Wüster,
PRA **99** 043616 (2019)



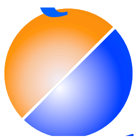
(II) BEC response to Rydberg insertion



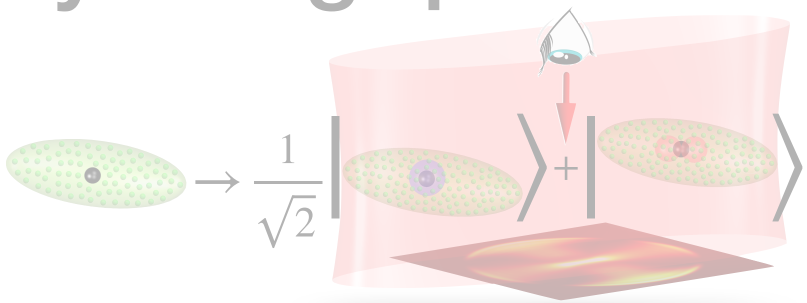


S. Tiwari *et al.* in preparation (2021).

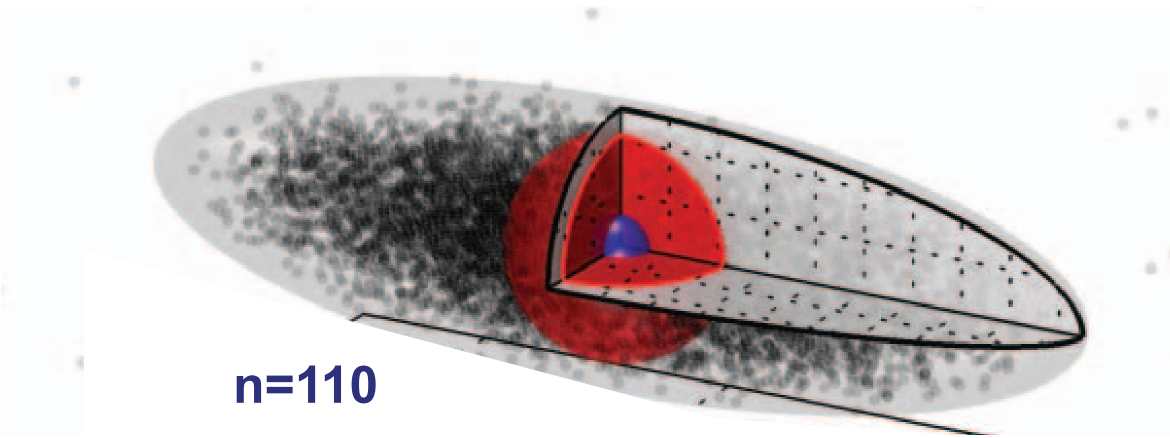
(III) Decoherence of Rydberg qubits in a BEC



S. Rammohan *et al.*
arXiv:2011.11022 (2020).
arXiv:2006.15376 (2020).



Rydbergs in BEC



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Nature **502** (2013) 664.

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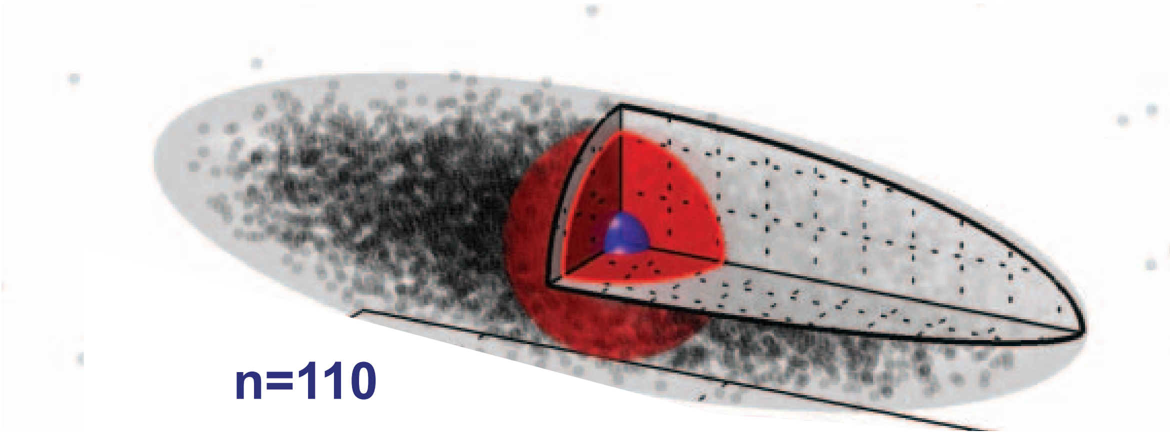

n=110

n=202

J. Balewski *et al.*,
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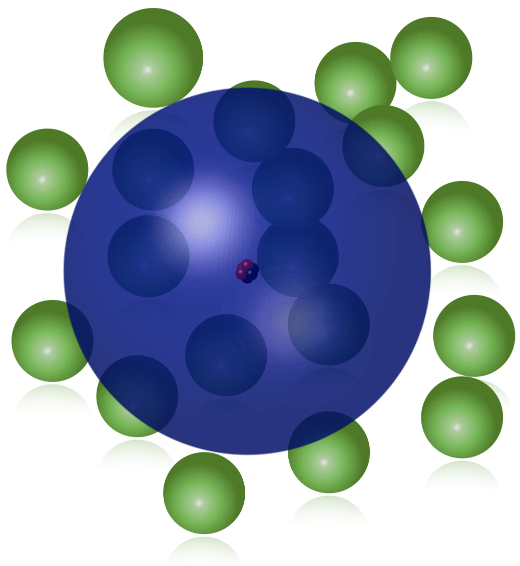
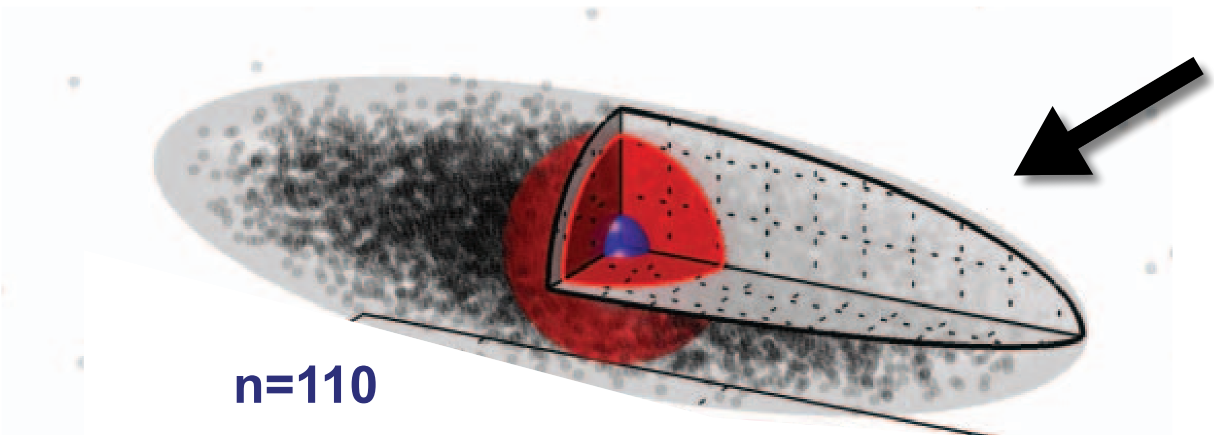


Rydbergs in BEC

$T \sim$ **nK**



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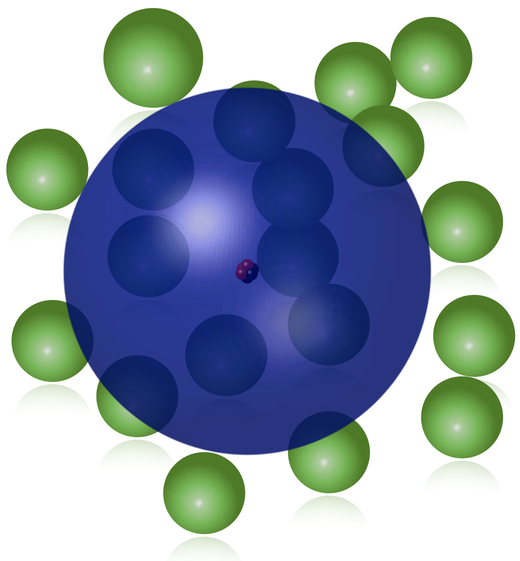
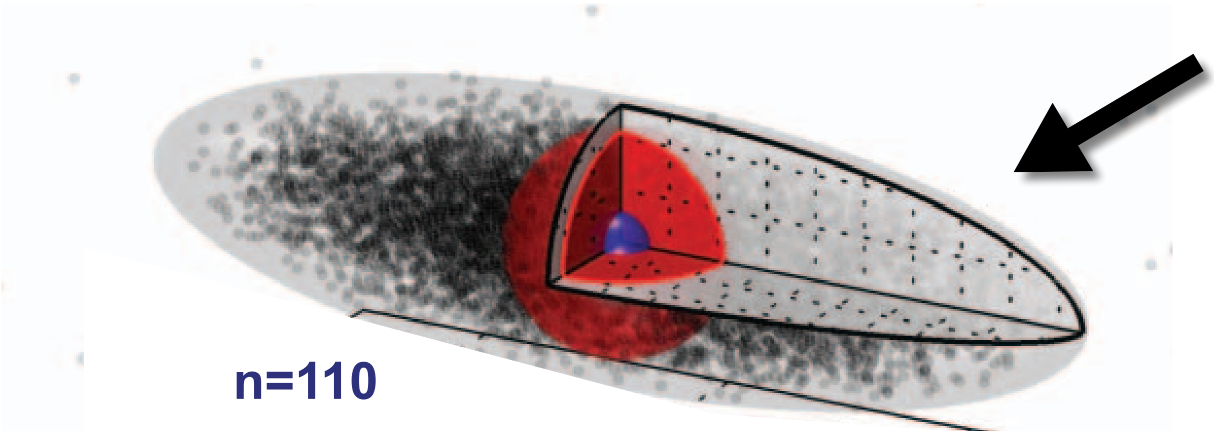


Rydbergs in BEC



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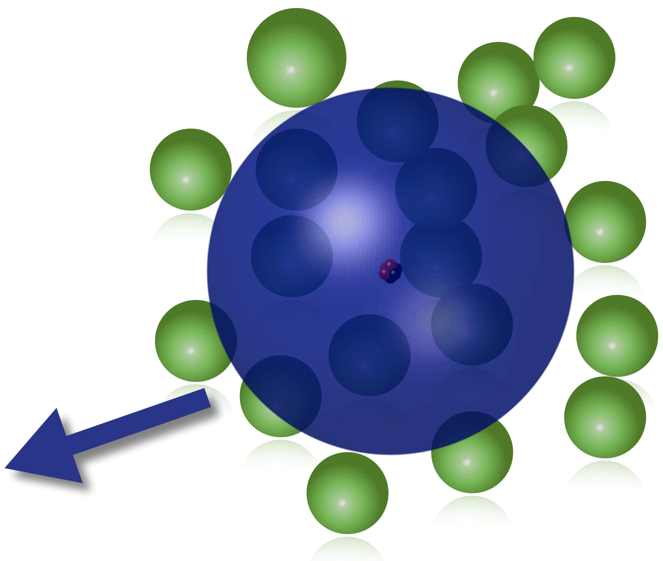
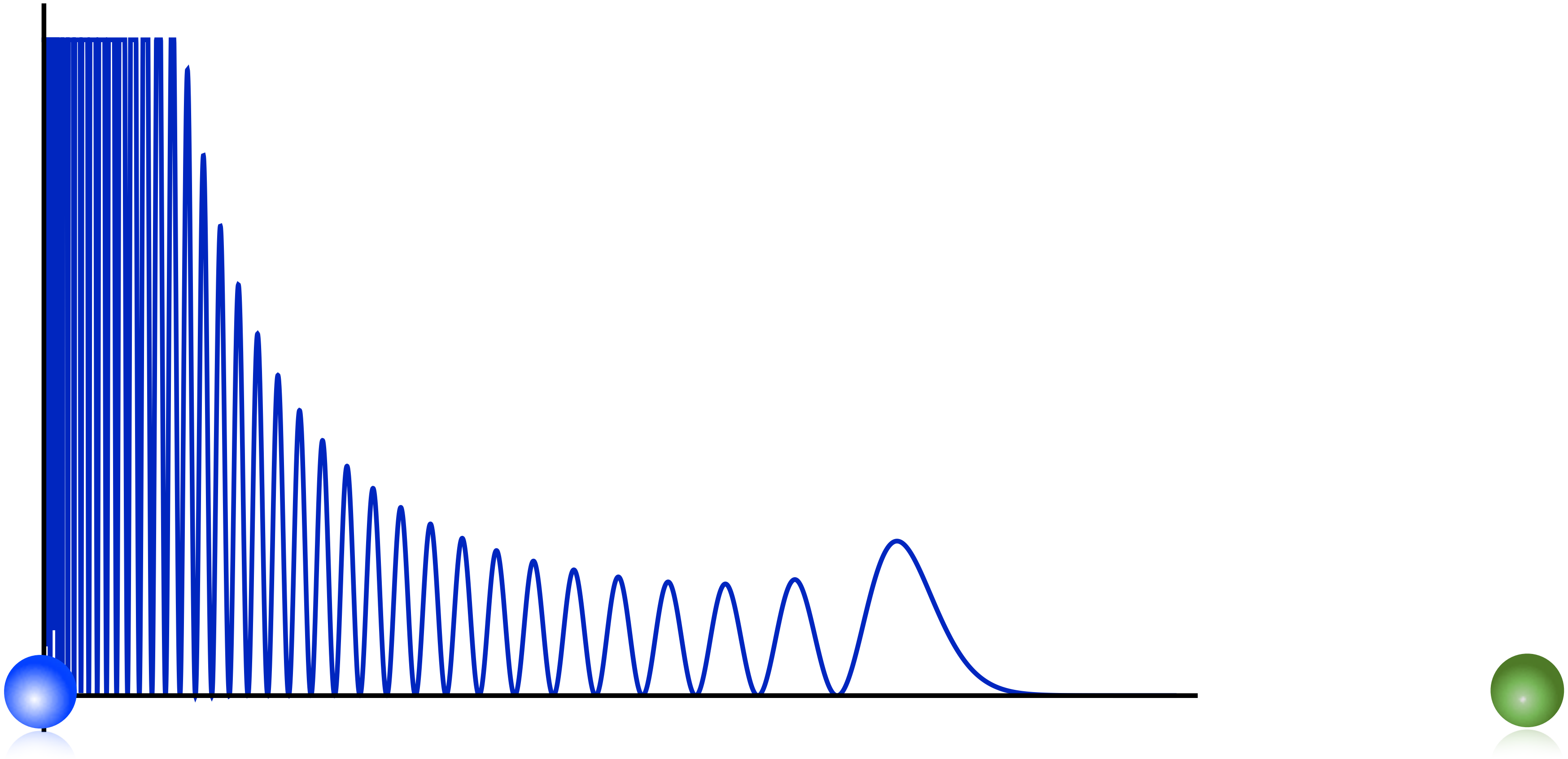


Intact Rydberg atom, with moderately reduced lifetime (1/2…1/10)

M. Schlagmüller *et al.*,
PRX **6** (2016) 031020.

S. Kanungo *et al.*,
PRA **102** (2020) 063317.

Interactions with ground-state atoms



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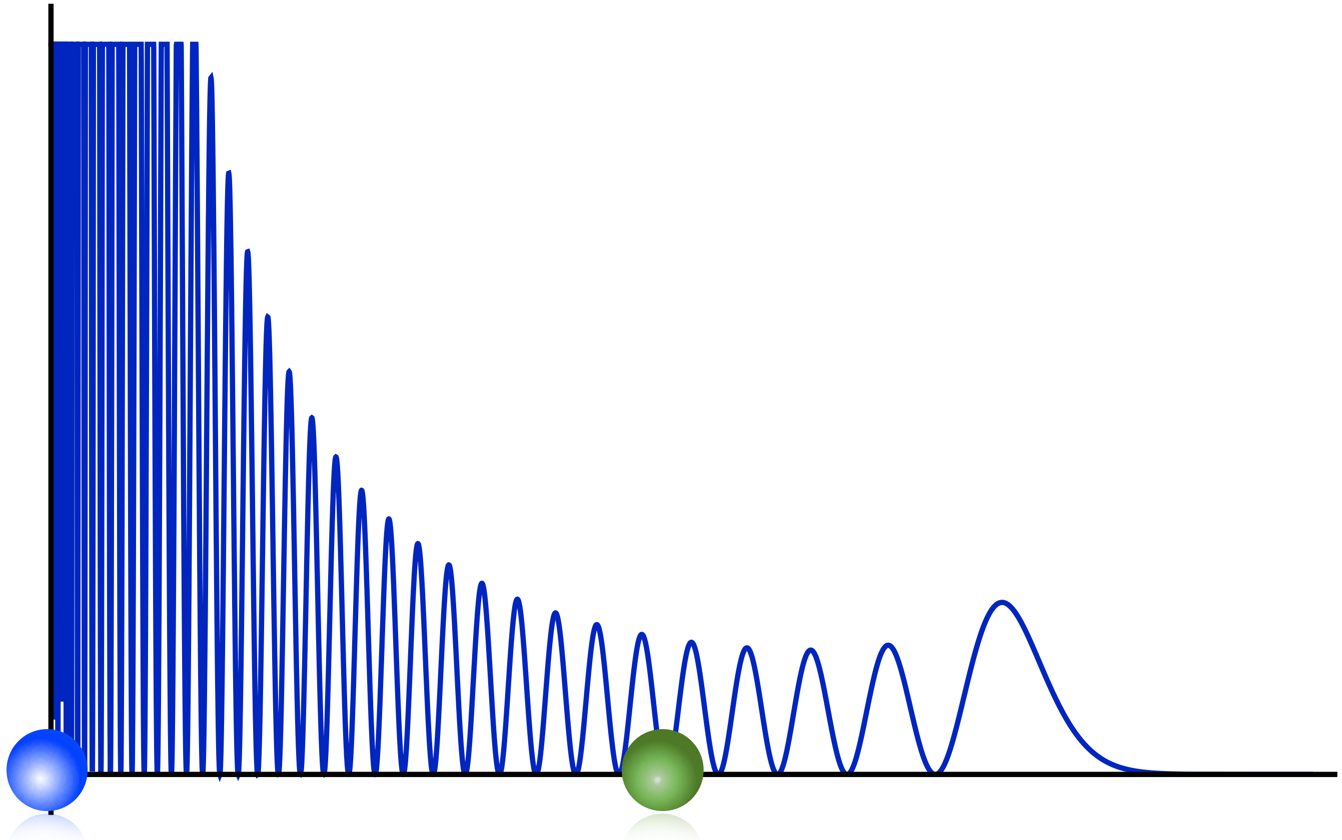
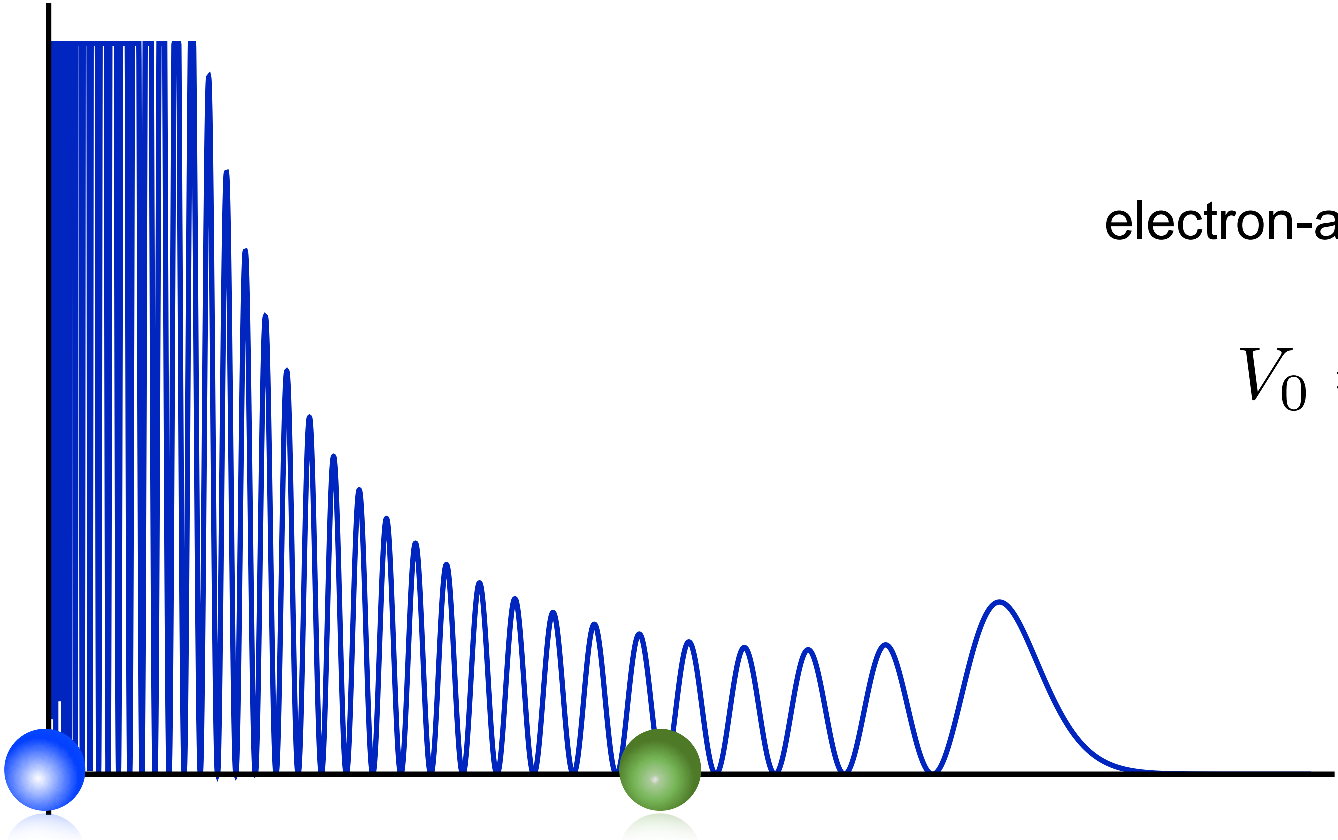


Ground-state atom **within Rydberg orbit**

Interactions with ground-state atoms



electron-atom s-wave scattering

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

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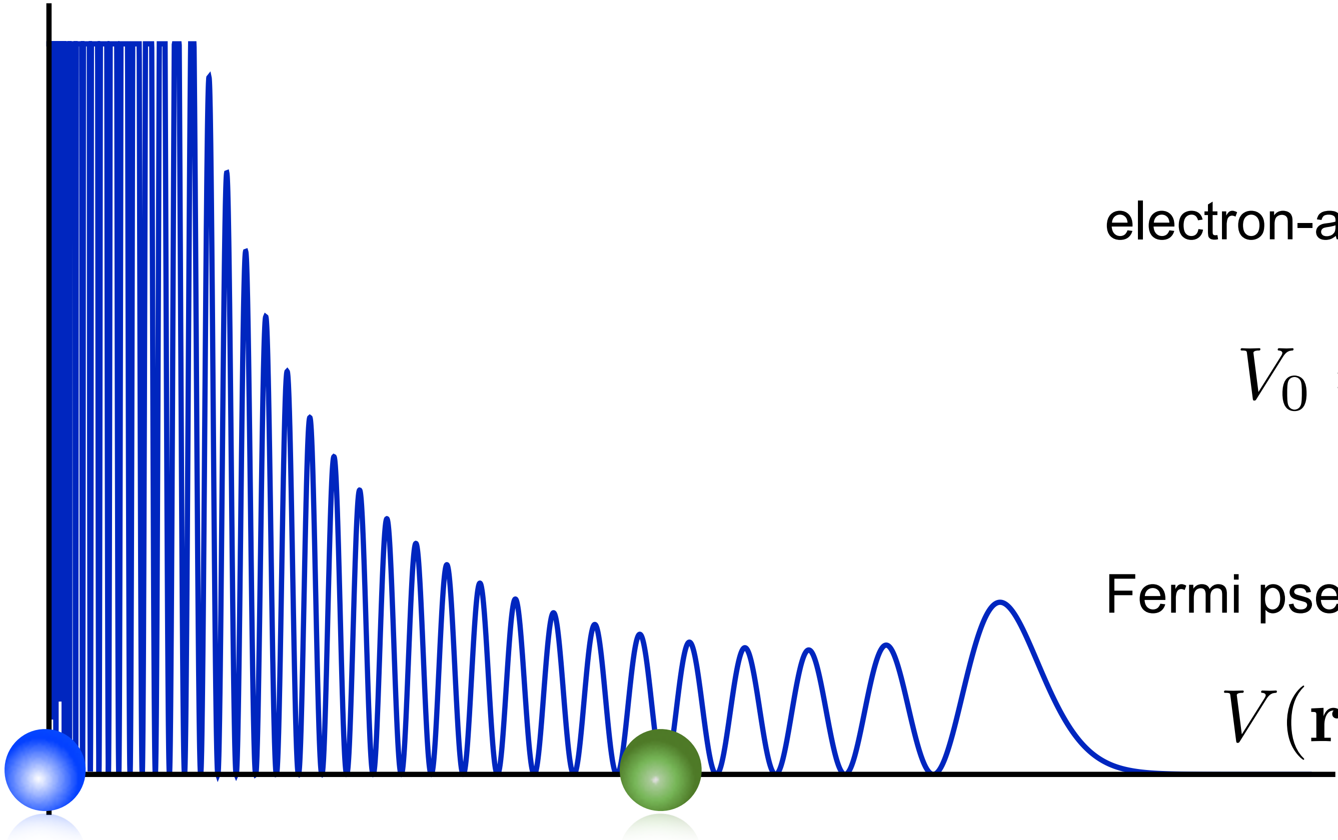
Interactions with ground-state atoms



electron-atom s-wave scattering

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

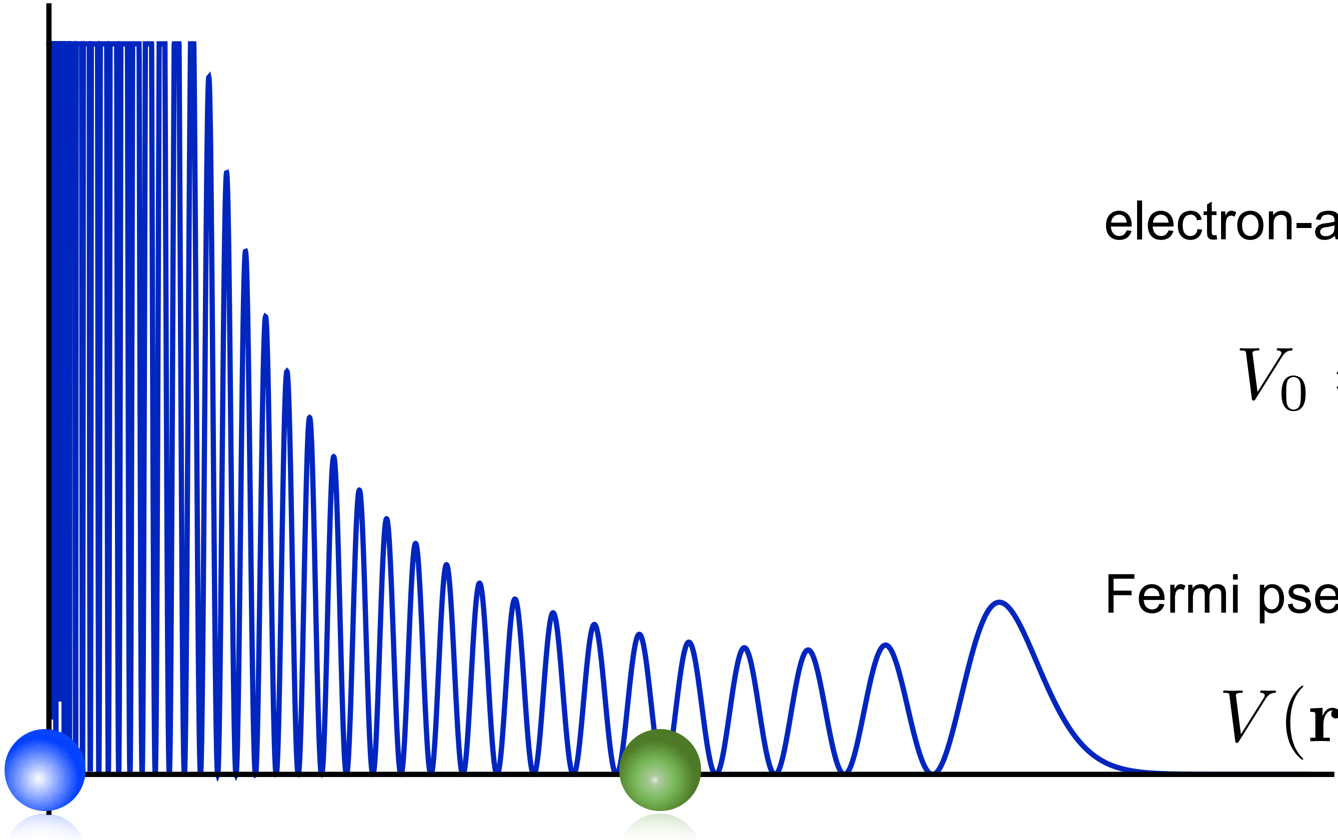
Fermi pseudo potential

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

Ground-state atom **within Rydberg orbit**

see e.g. C.H. Greene *et al.*
PRL **85** (2000) 2458

Interactions with ground-state atoms



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Fermi pseudo potential

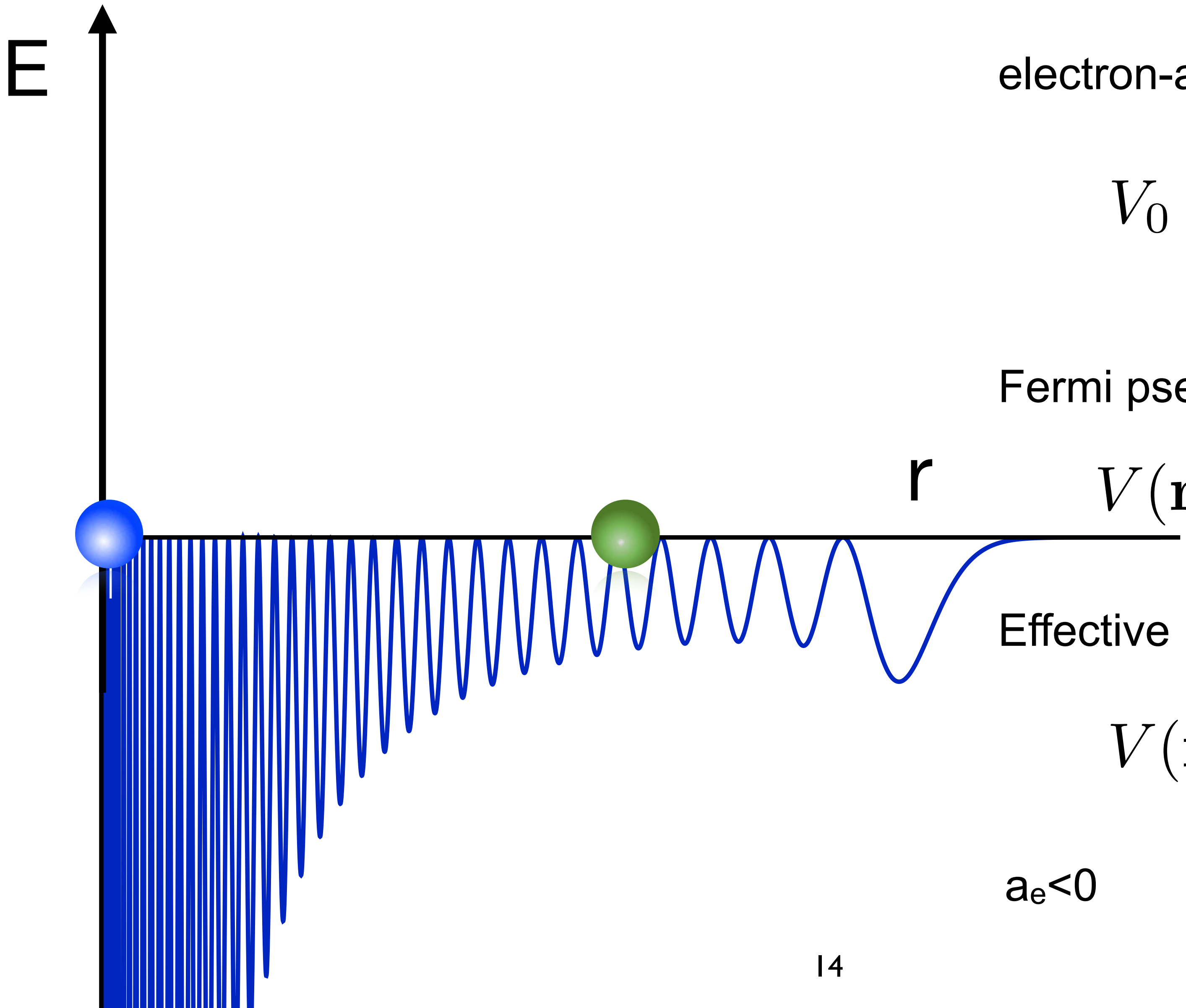
$$V(\mathbf{r}) = V_0\delta(\mathbf{x}_e - \mathbf{r})$$

Effective Rydberg-GS potential

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

$a_e<0$

Interactions with ground-state atoms



electron-atom s-wave scattering

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

Fermi pseudo potential

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

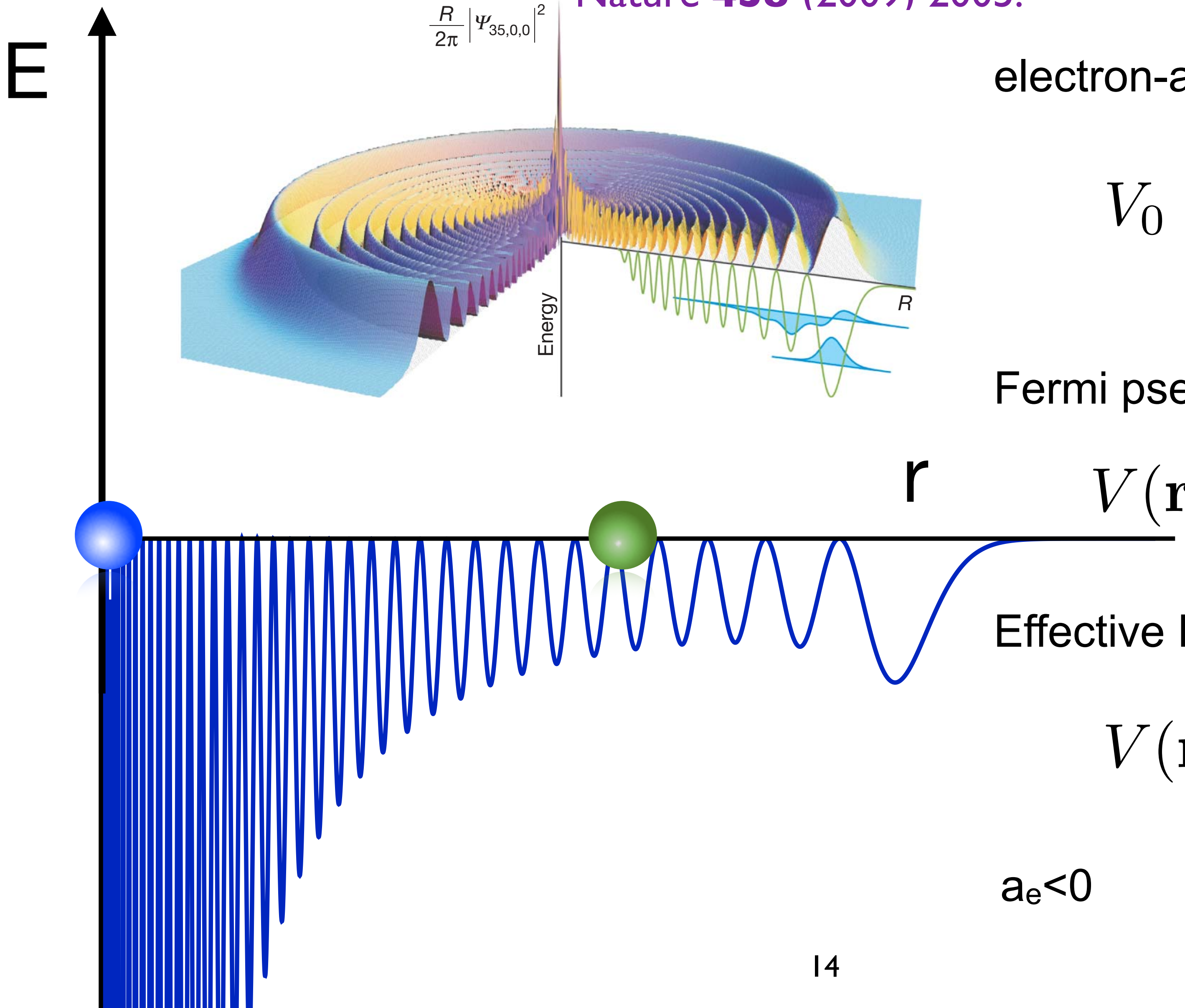
Effective Rydberg-GS potential

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

$a_e<0$

Interactions with ground-state atoms

Figure from: V. Bendkowsky *et al.* Nature **458** (2009) 2005.



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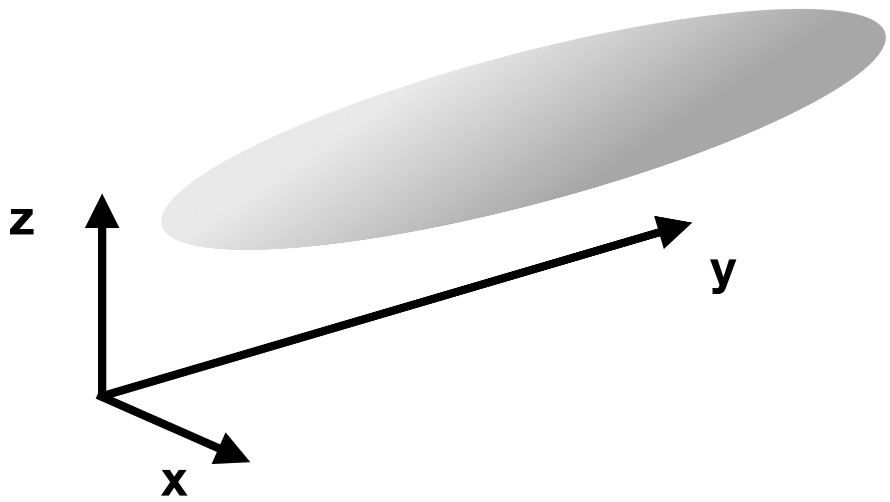
Rydbergs in BEC

Gross Pitaevskii equation

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



Rydbergs in BEC

Gross Pitaevskii equation with impurities

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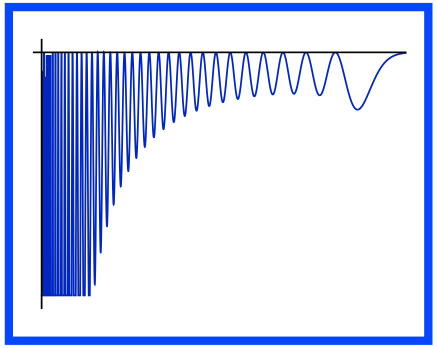

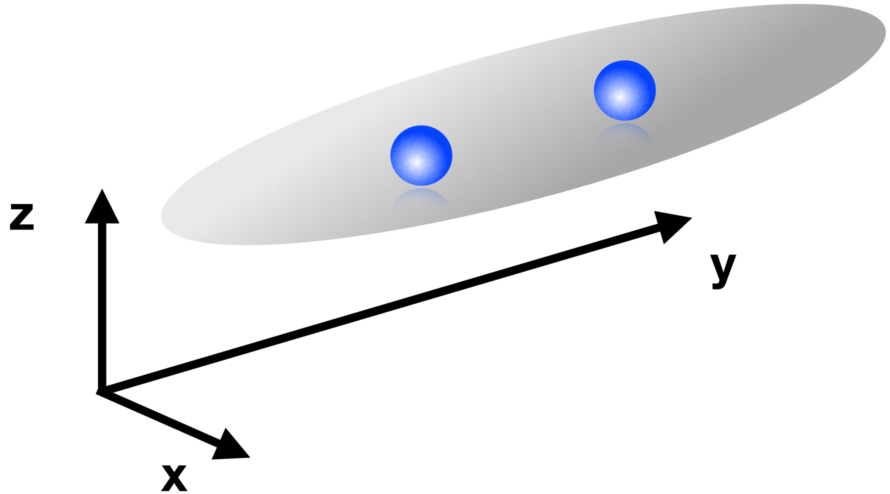

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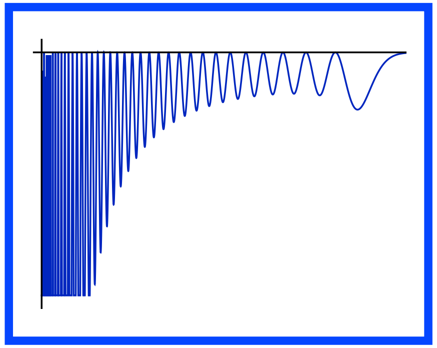
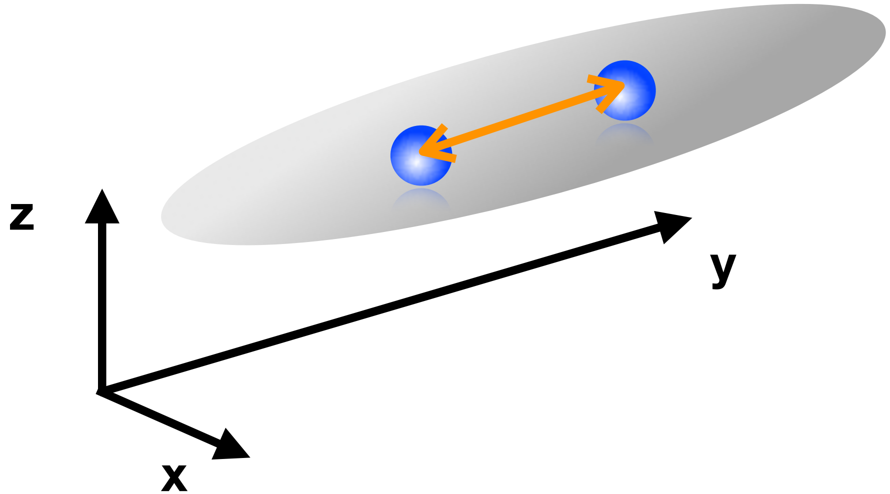


Newton's equations with vdW interactions

$$m\frac{\partial^2}{\partial t^2}\mathbf{x}_n = -\nabla_{\mathbf{x_n}} \sum_{n>m} \frac{C_6(\nu)}{|\mathbf{x}_n - \mathbf{x}_m|^6}$$



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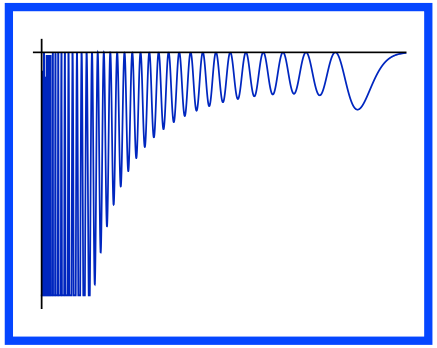

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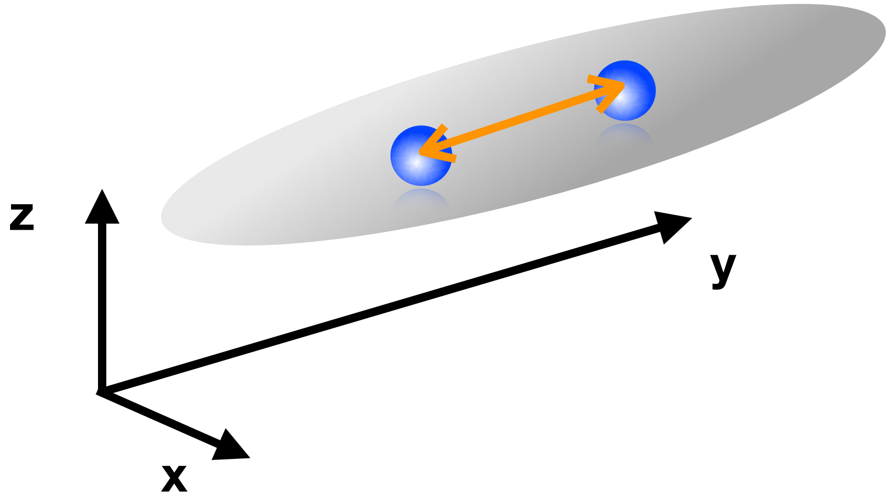

Initially: Phase imprinting

Rydbergs in BEC

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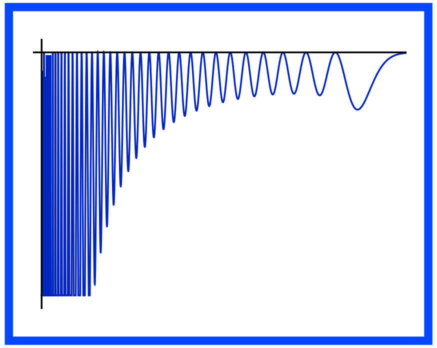
$$i\hbar \frac{\partial}{\partial t}\phi(\mathbf{R}) = \qquad + \sum_{n}^{N_{imp}} V_0 |\Psi(\mathbf{R}-\mathbf{x}_n)|^2 \Big) \phi(\mathbf{R})$$



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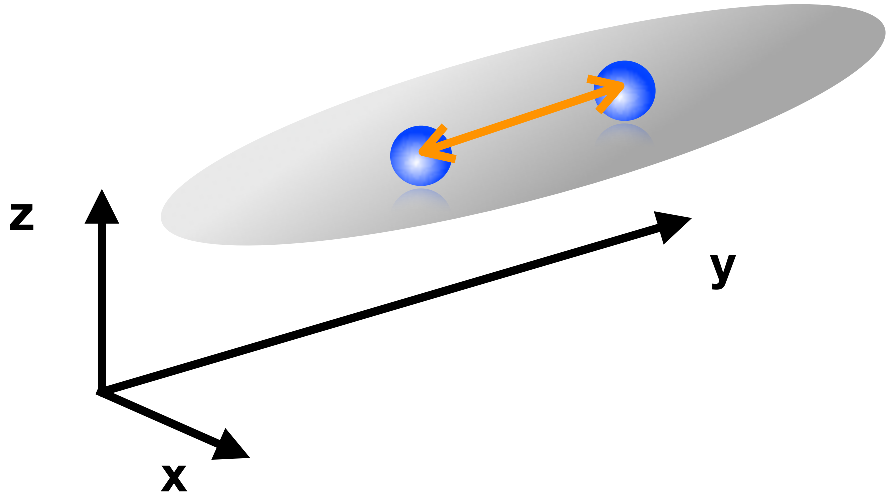

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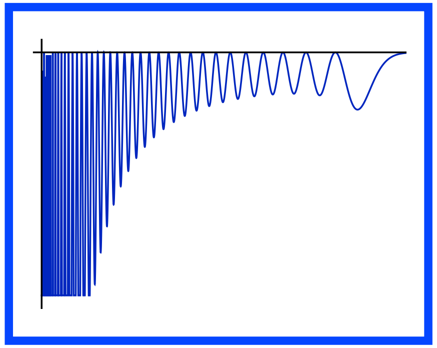

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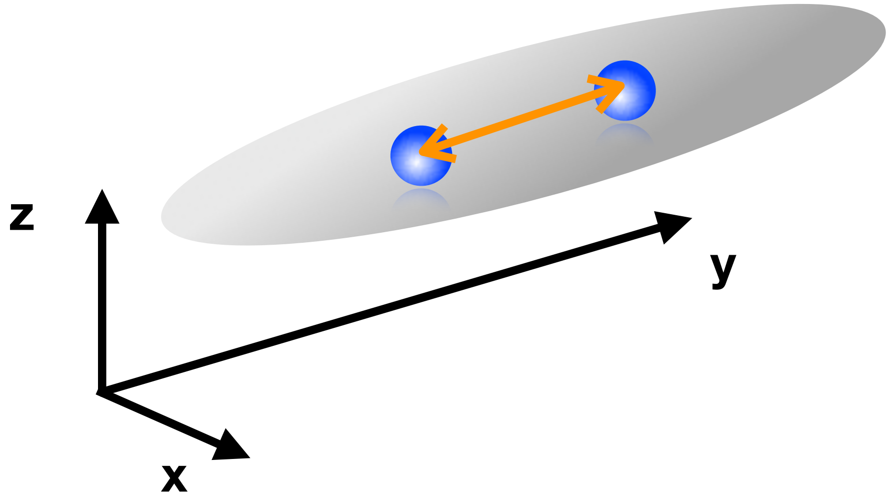

Initially: Phase imprinting

$$\phi(\mathbf{R},t) = \phi(\mathbf{R},0)\; e^{-i\sum_n^{N_{imp}} V_0|\Psi(\mathbf{R}-\mathbf{x}_n)|^2 t/\hbar}$$

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

Phase imprinting tracks

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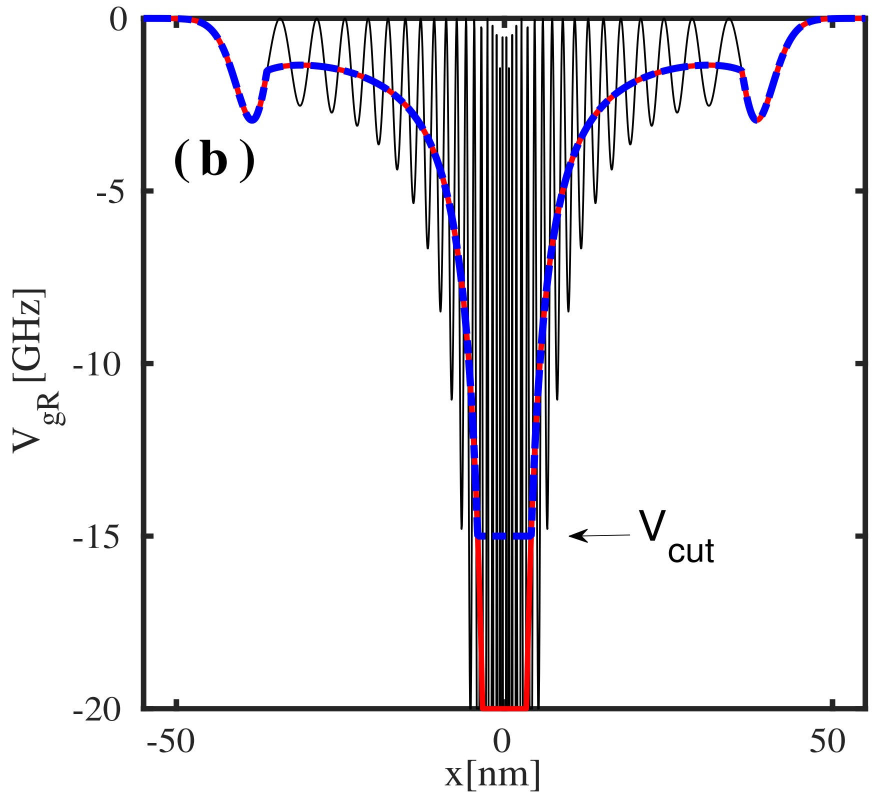

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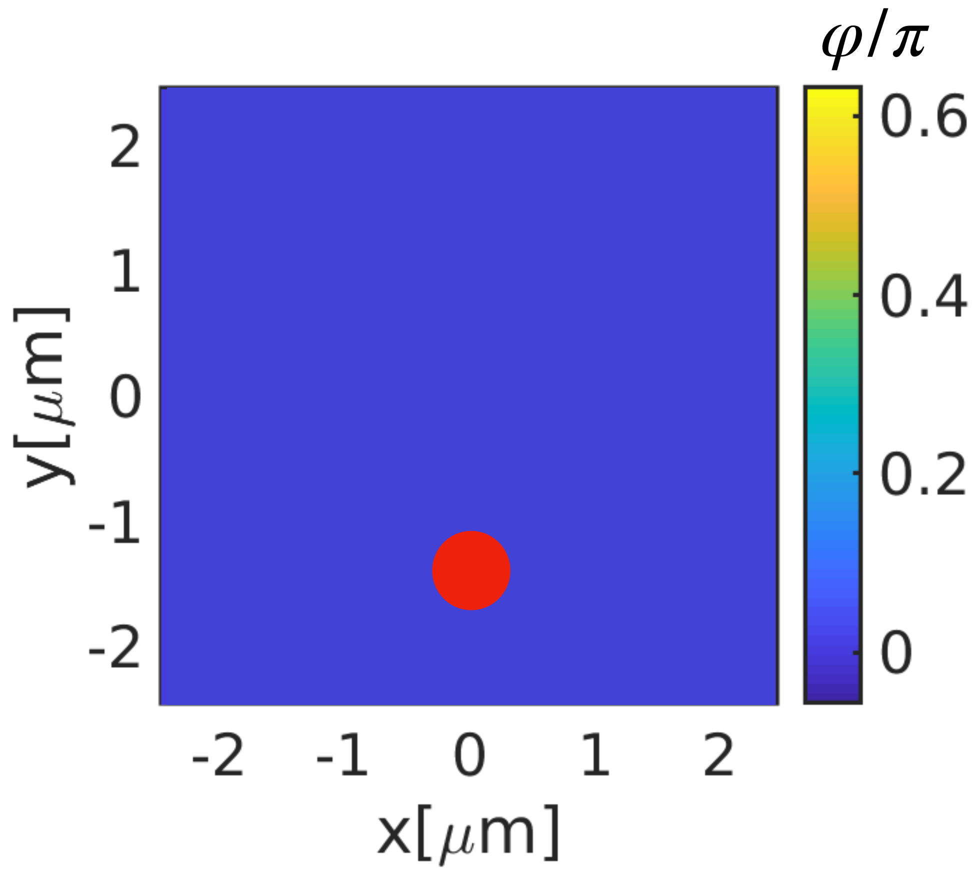

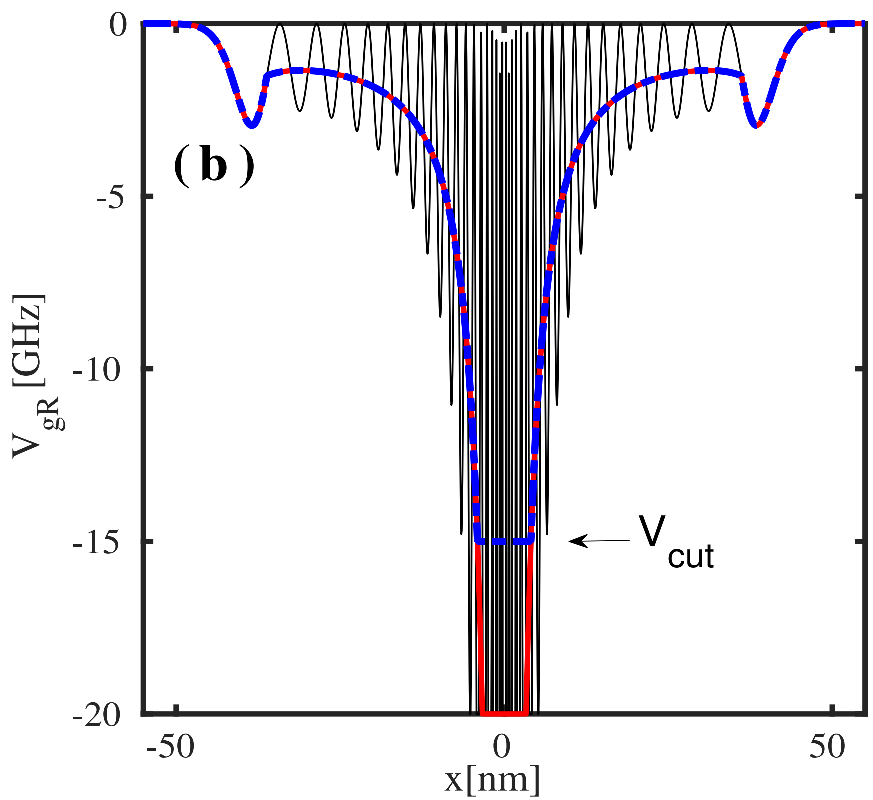

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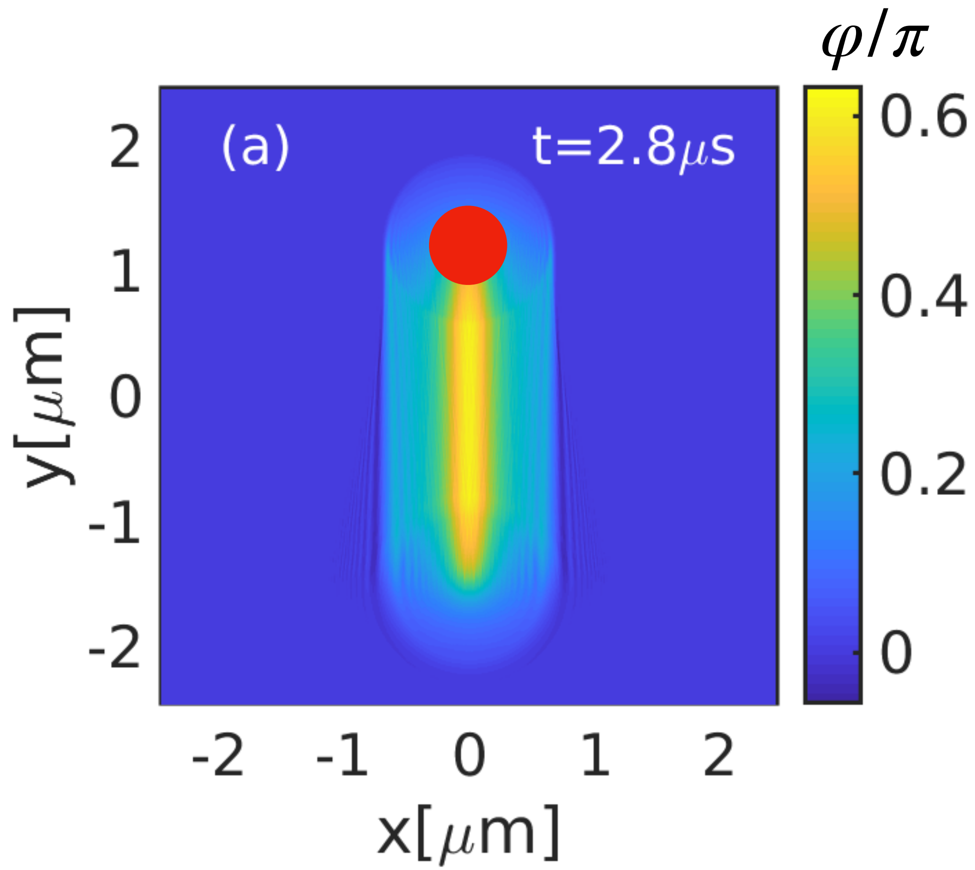
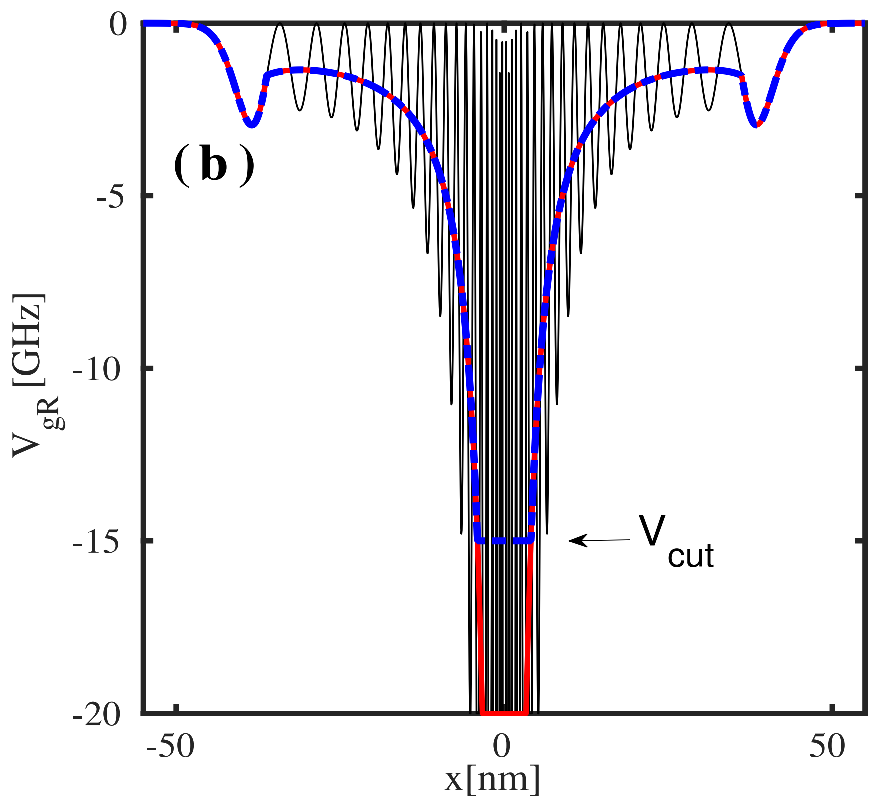
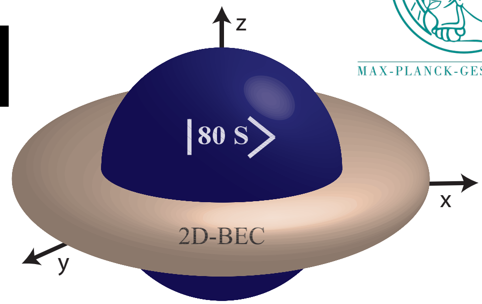
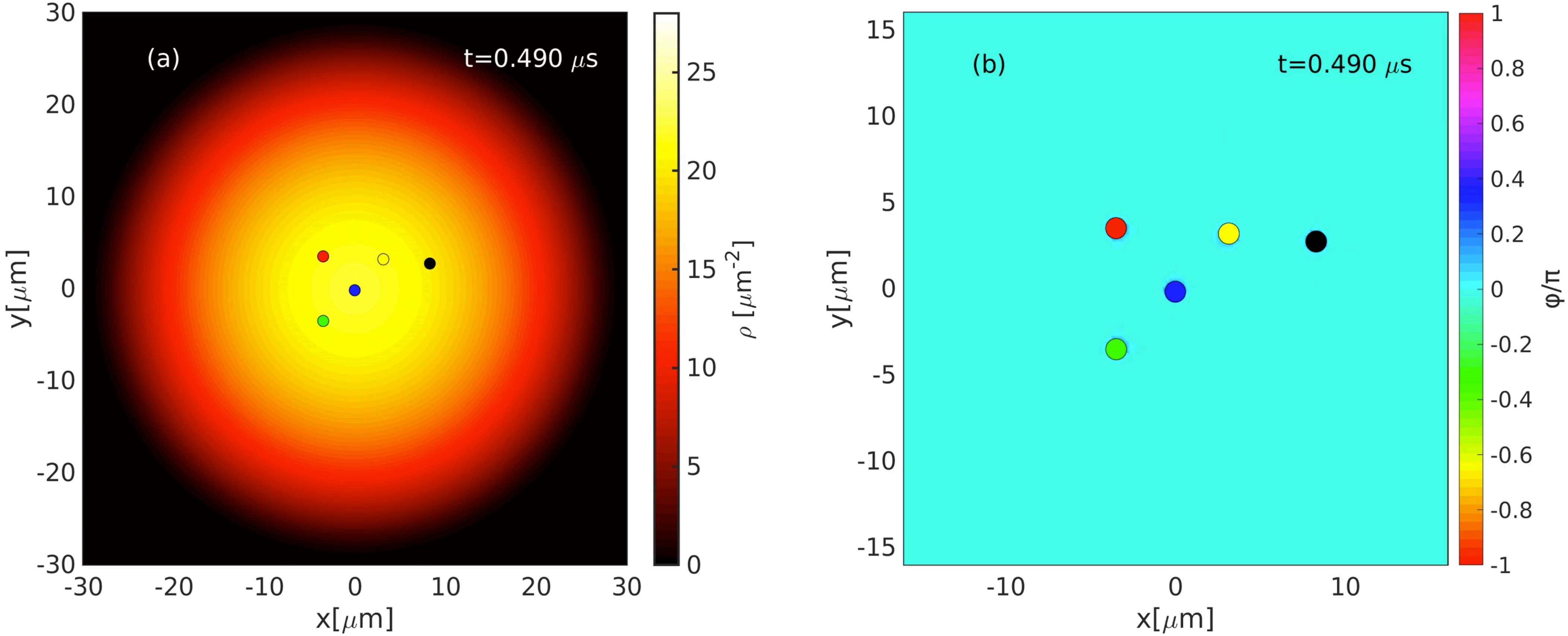




GPE (2D) extended





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

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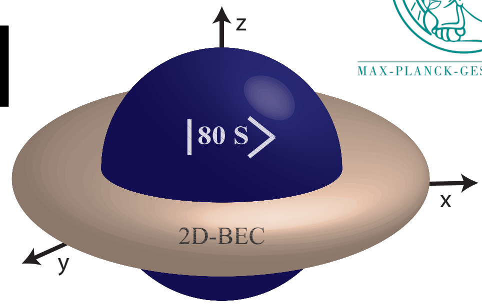
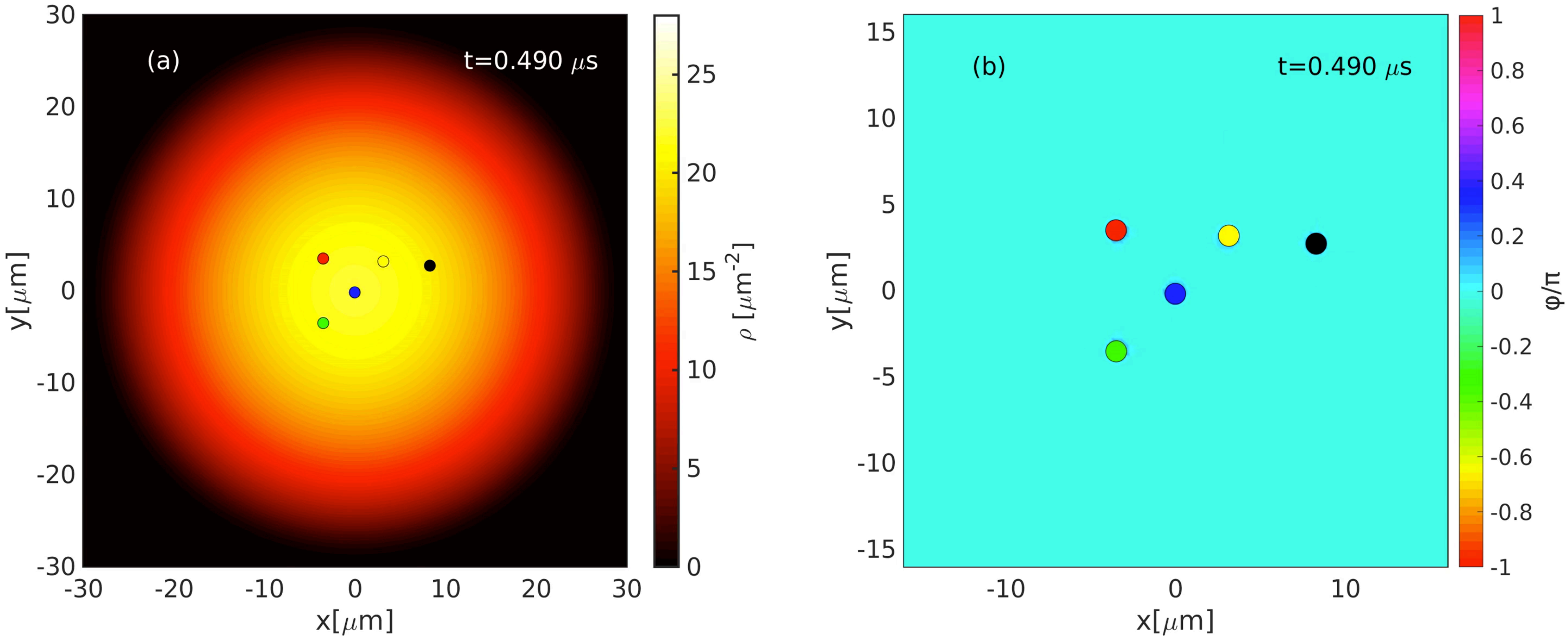
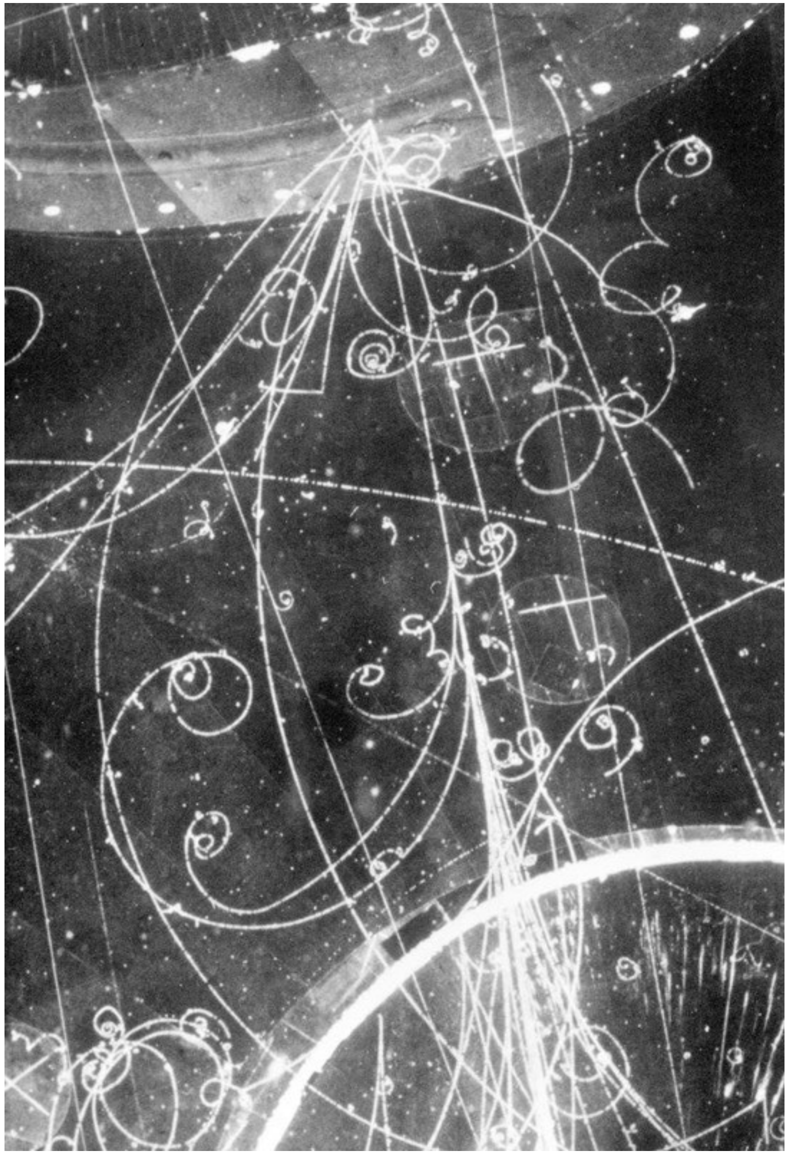


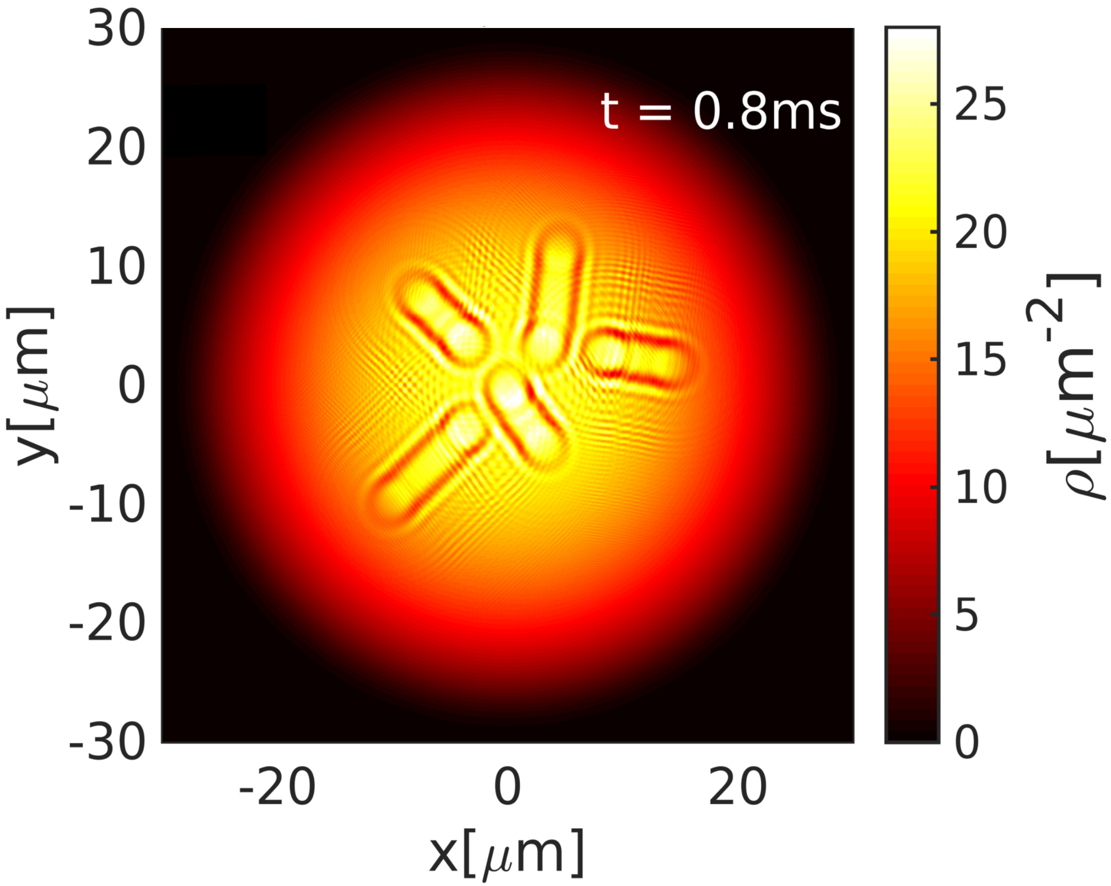


S. Tiwari and S. Wüster,
PRA **99** 043616 (2019)

Rydberg “Bubble chamber”



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



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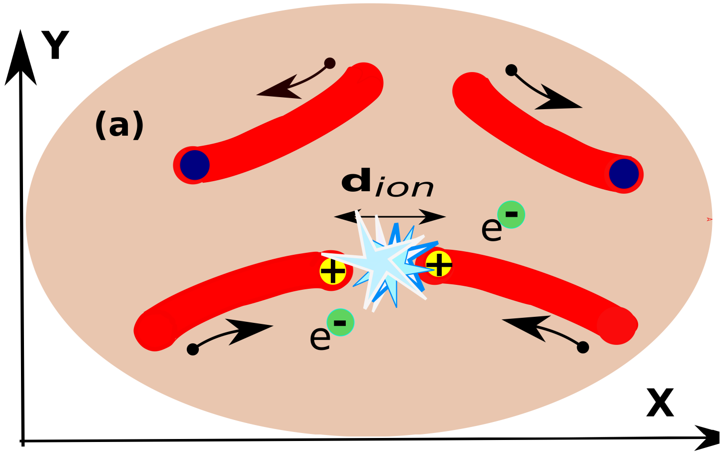
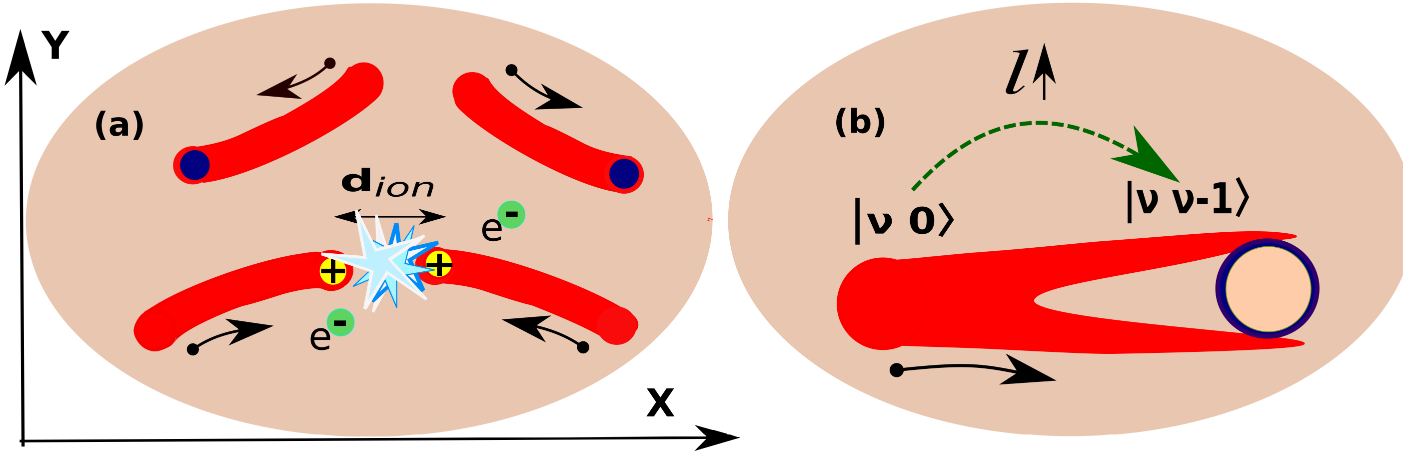


Ionizing collisions terminate tracks?

T. Amthor *et al.*,
PRL **98** (2007) 023004.

Rydberg “Bubble chamber”



Ionizing collisions terminate tracks?

l-changing collisions reshape tracks?

T. Amthor *et al.*,
PRL **98** (2007) 023004.

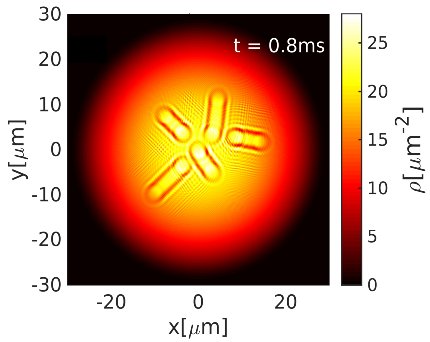
M. Schlagmüller *et al.*,
PRX **6** (2016) 031020.

T. Niederprüm *et al.*,
PRL **115** (2015) 013003.

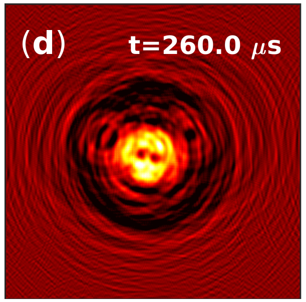
Outline

(I) Tracking of mobile Rydberg atoms in a BEC

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



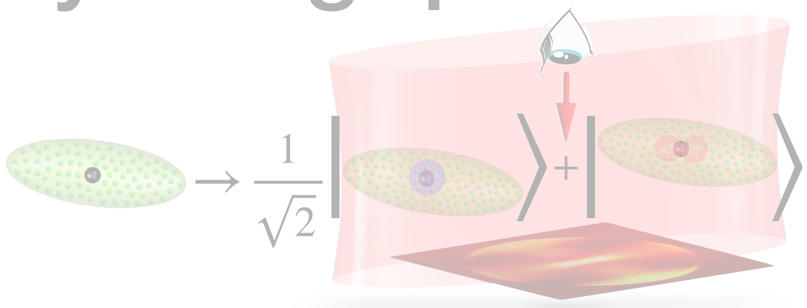
(II) BEC response to Rydberg insertion



S. Tiwari *et al.* in preparation (2021).

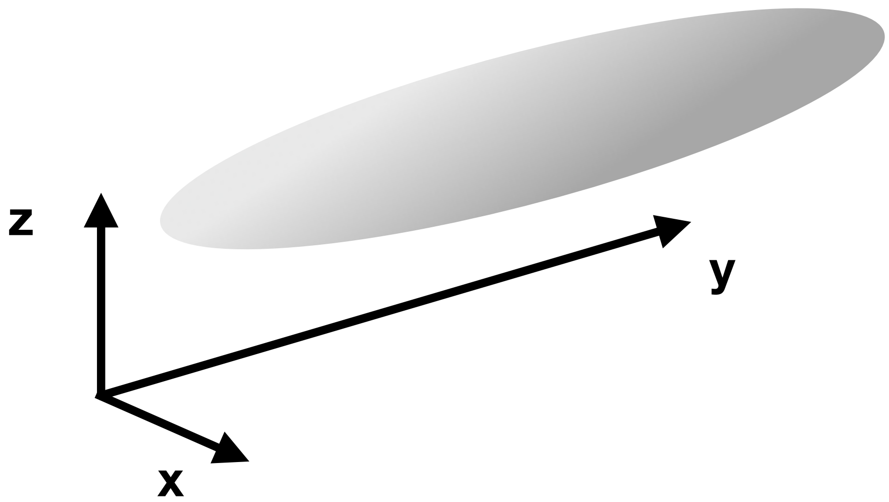
(III) Decoherence of Rydberg qubits in a BEC

S. Rammohan *et al.*
arXiv:2011.11022 (2020).
arXiv:2006.15376 (2020).



Experiments

In situ phase contrast imaging ⟹ BEC density change



Sequence

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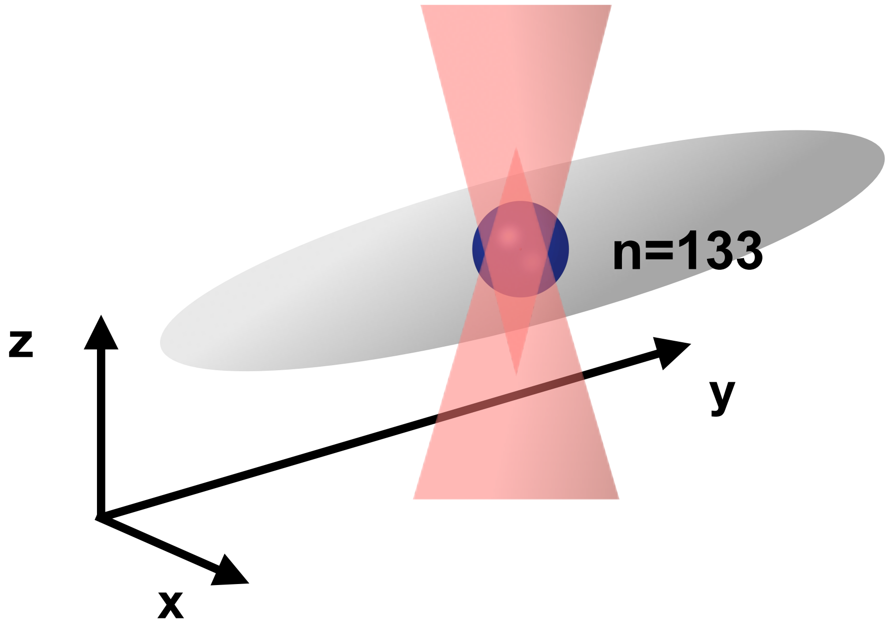

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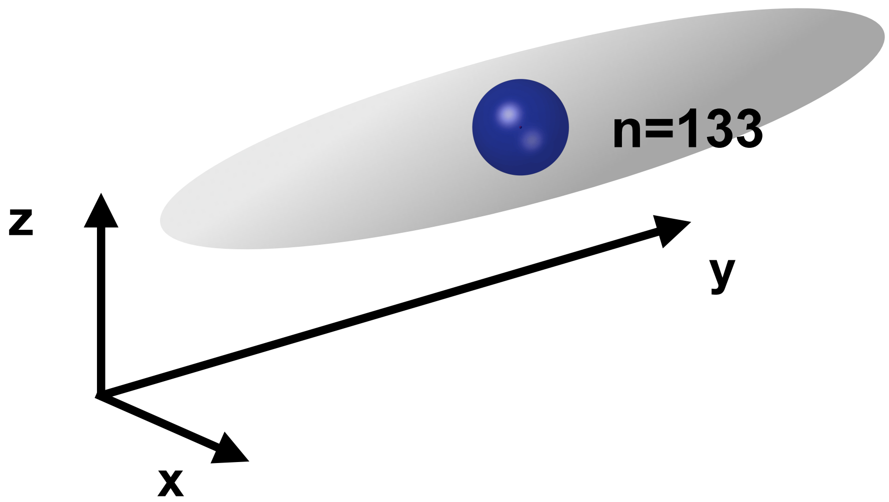

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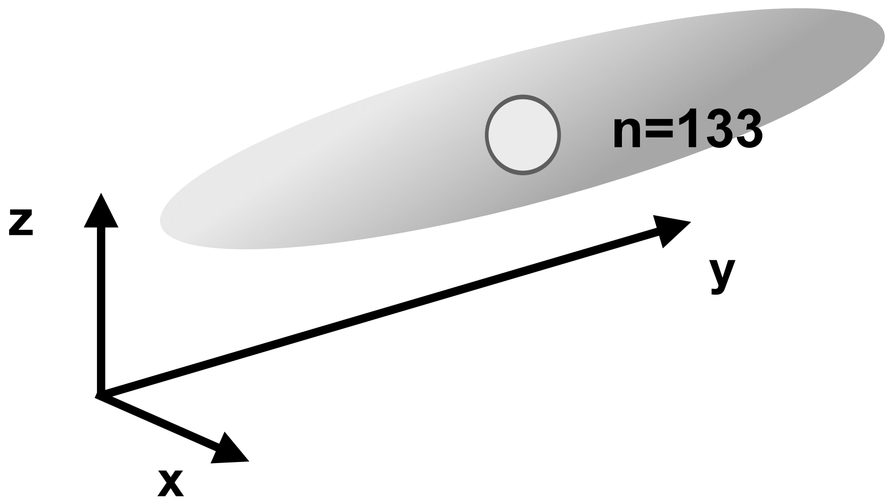

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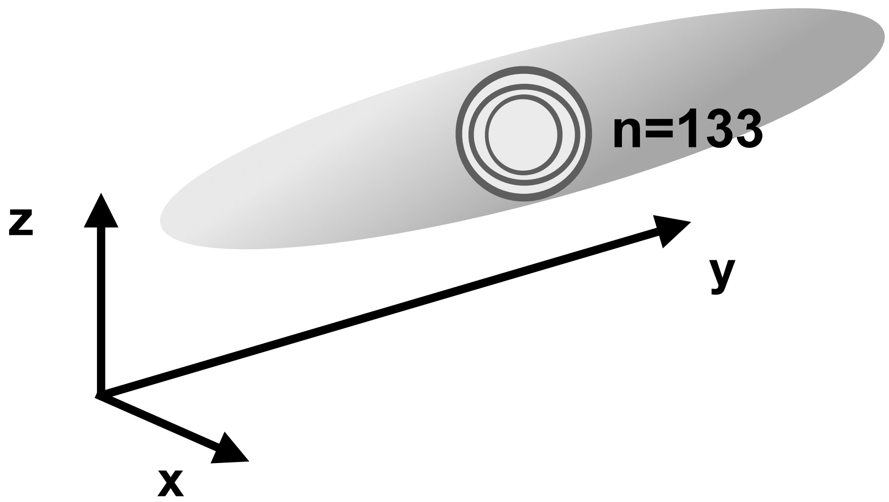

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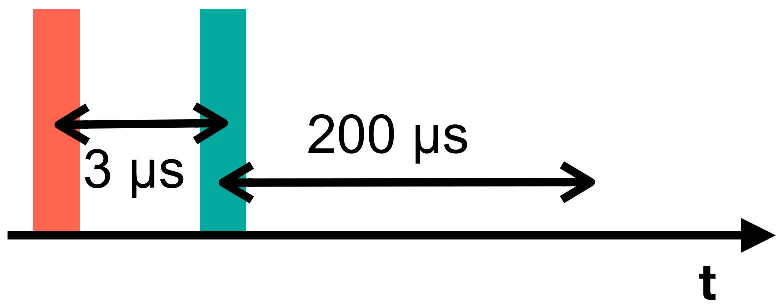

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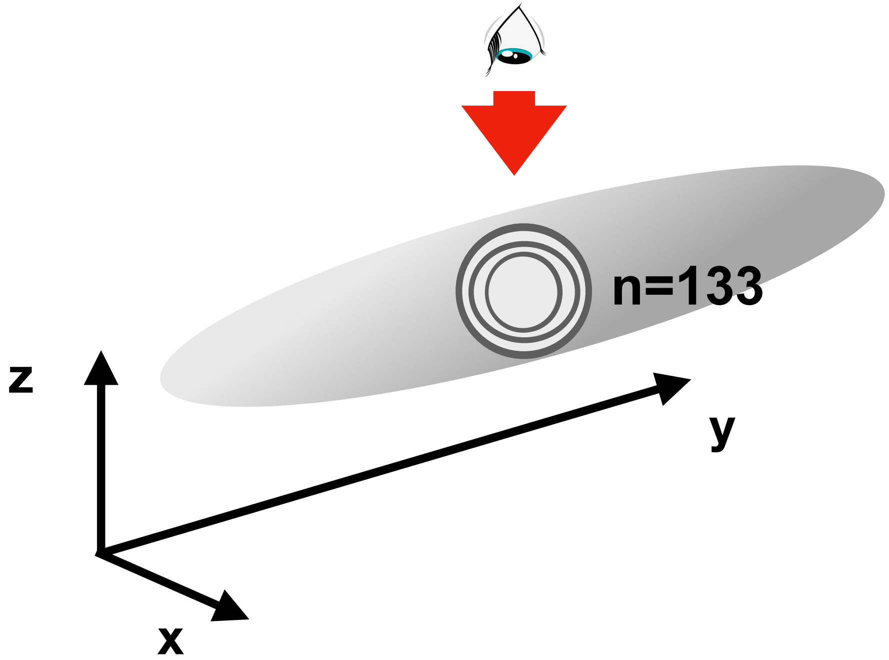

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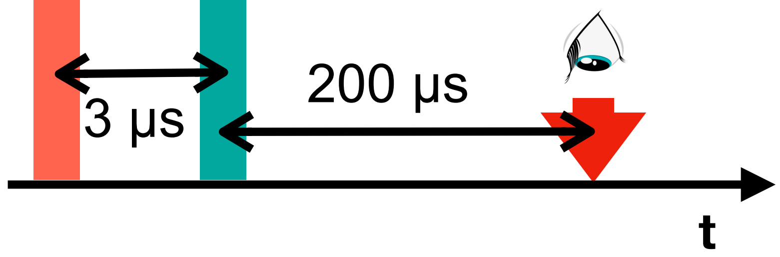

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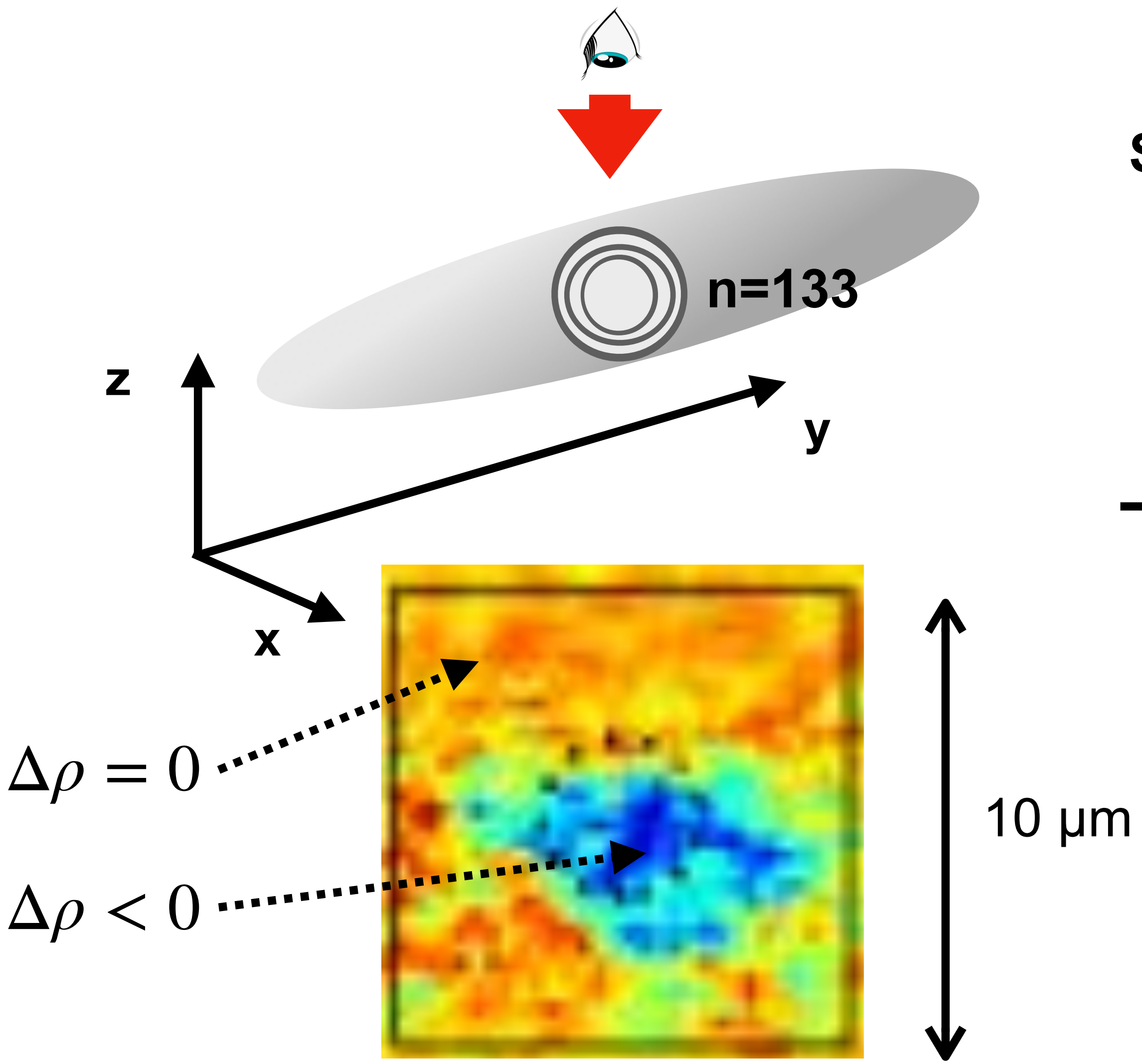
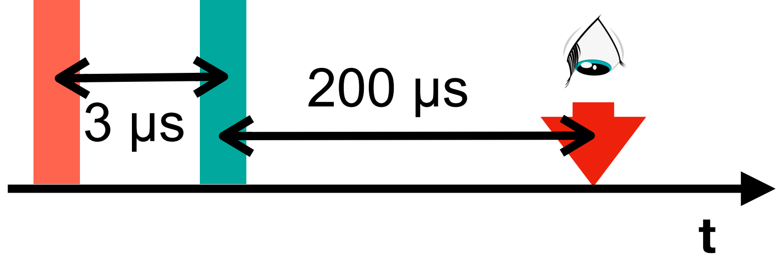


Single Rydberg

Sequence



Experimental images by Felix Engel and Florian Meinert, Univ. Stuttgart

Experiments

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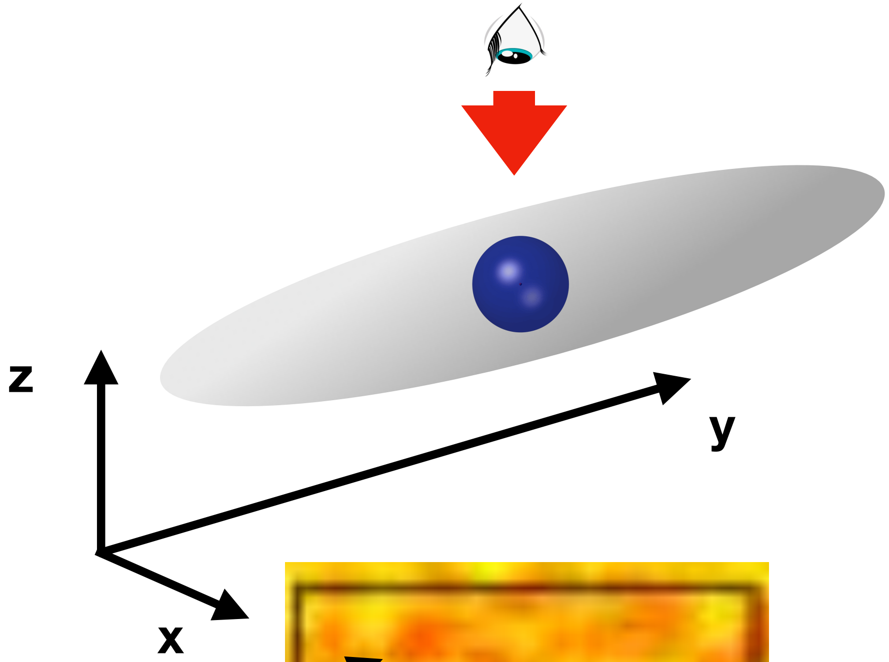

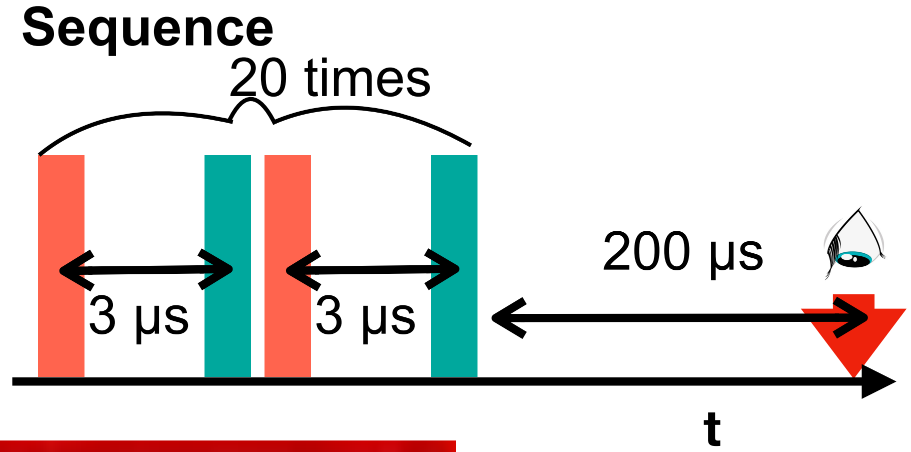

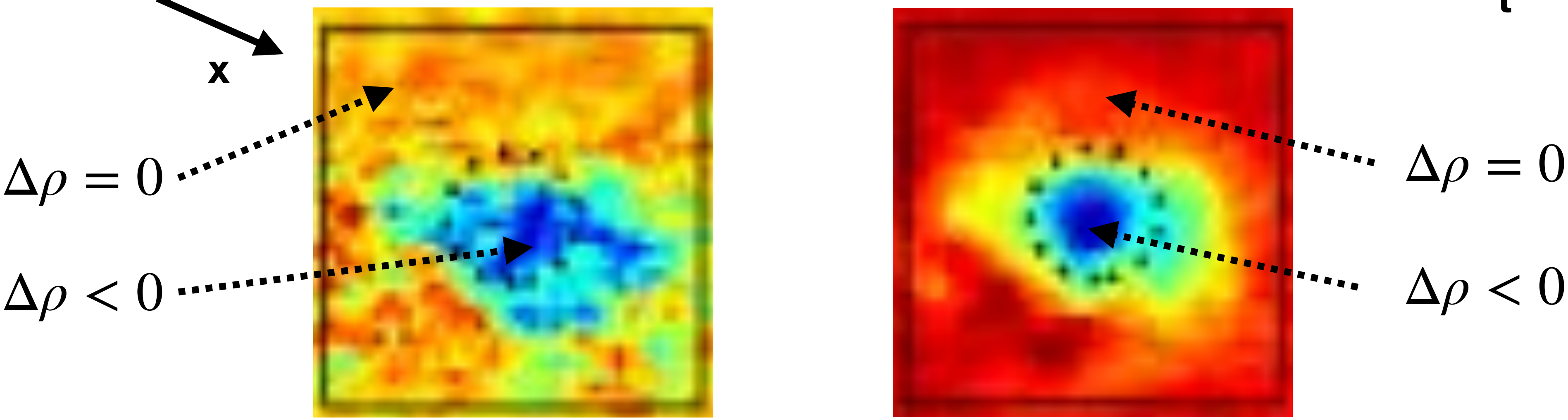

Single Rydberg for 3 μs

Wait 200 μs

20 Rydbergs for 3 μs each

Wait 200 μs

Experimental images by Felix Engel and Florian Meinert, Univ. Stuttgart

Simulations

GPE (3D) with randomized Rydberg location

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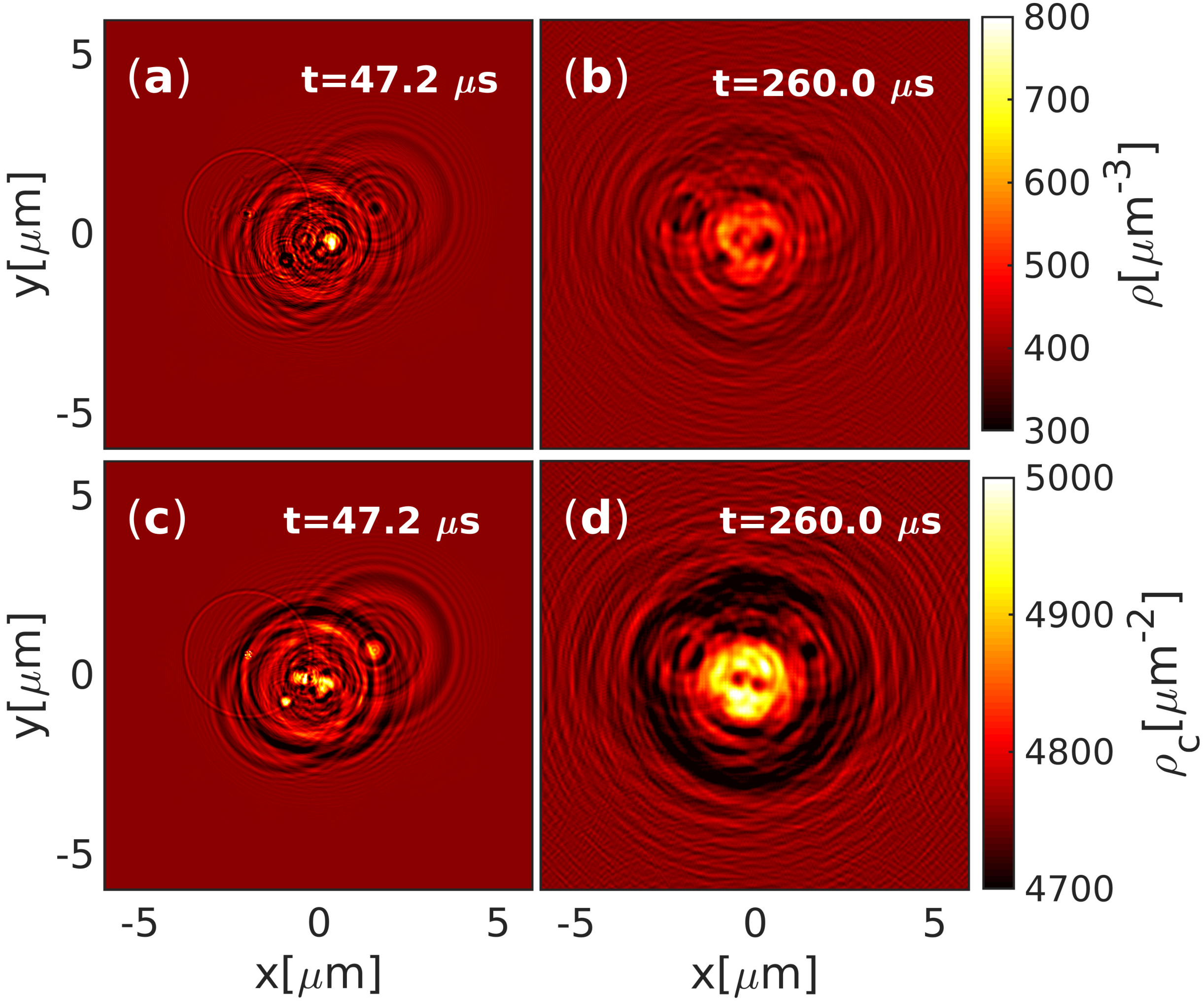

S. Tiwari *et al.*
in preparation (2021).

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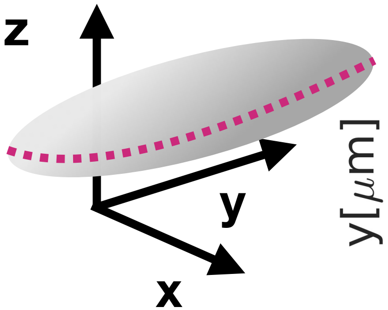

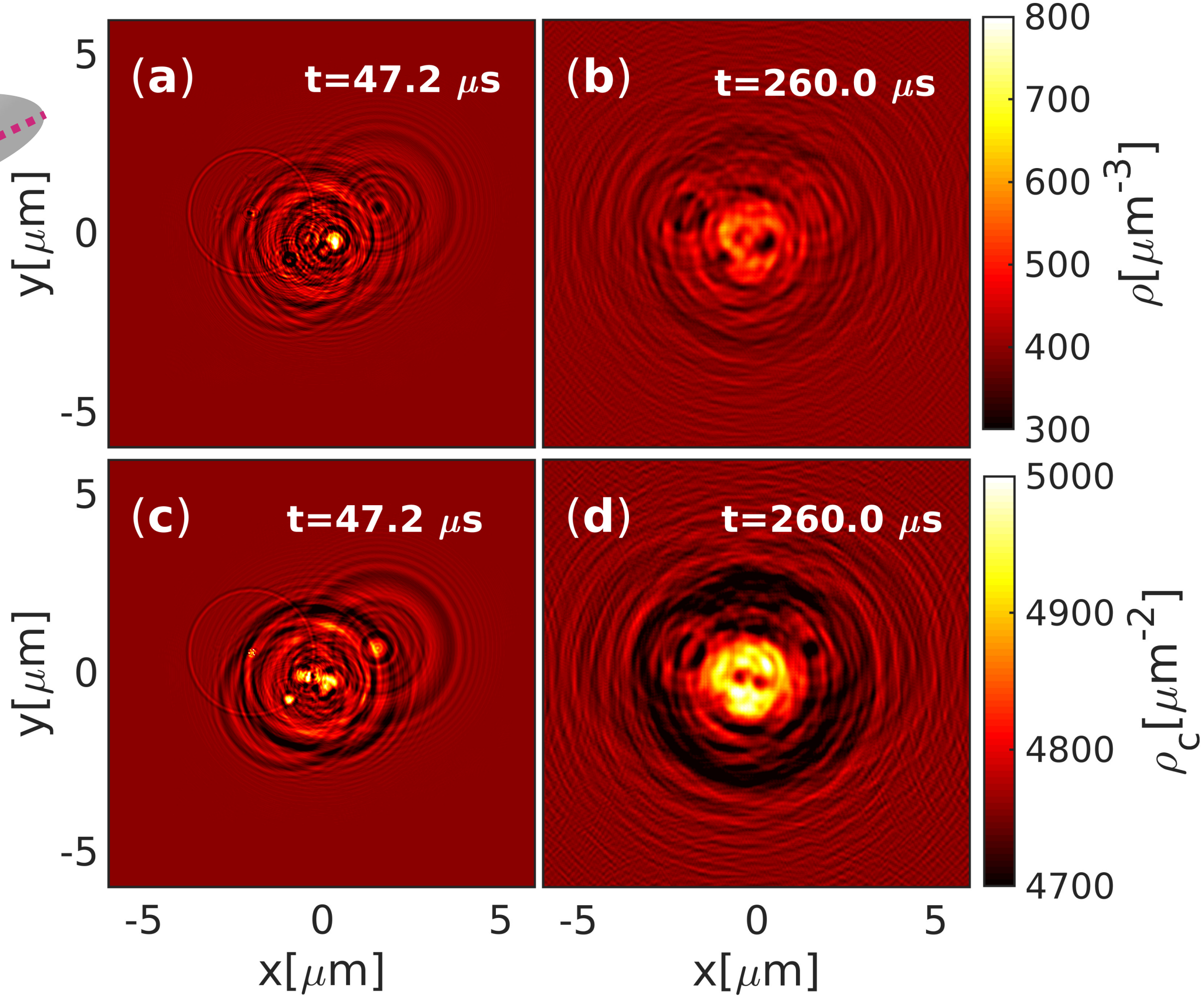

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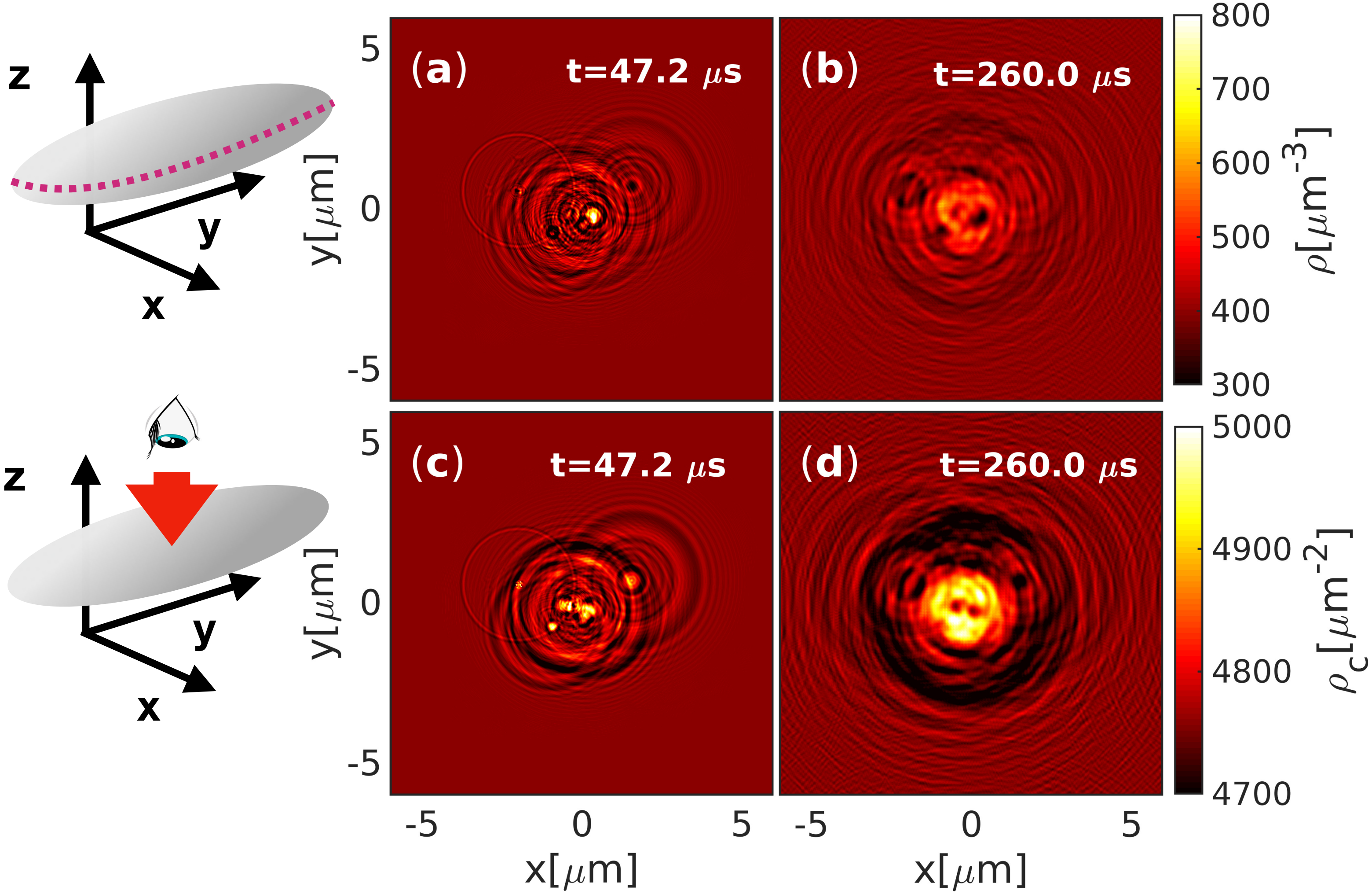

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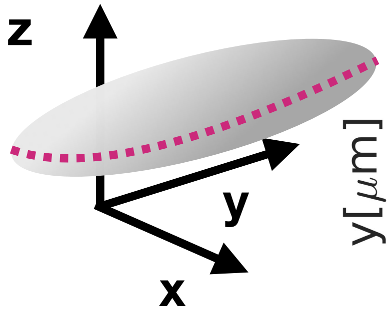
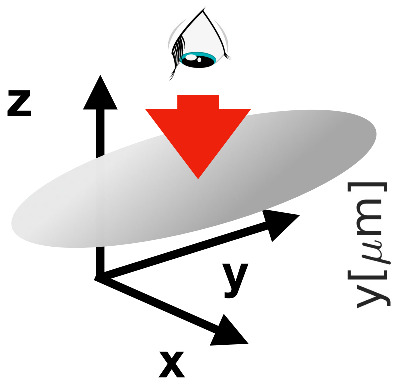
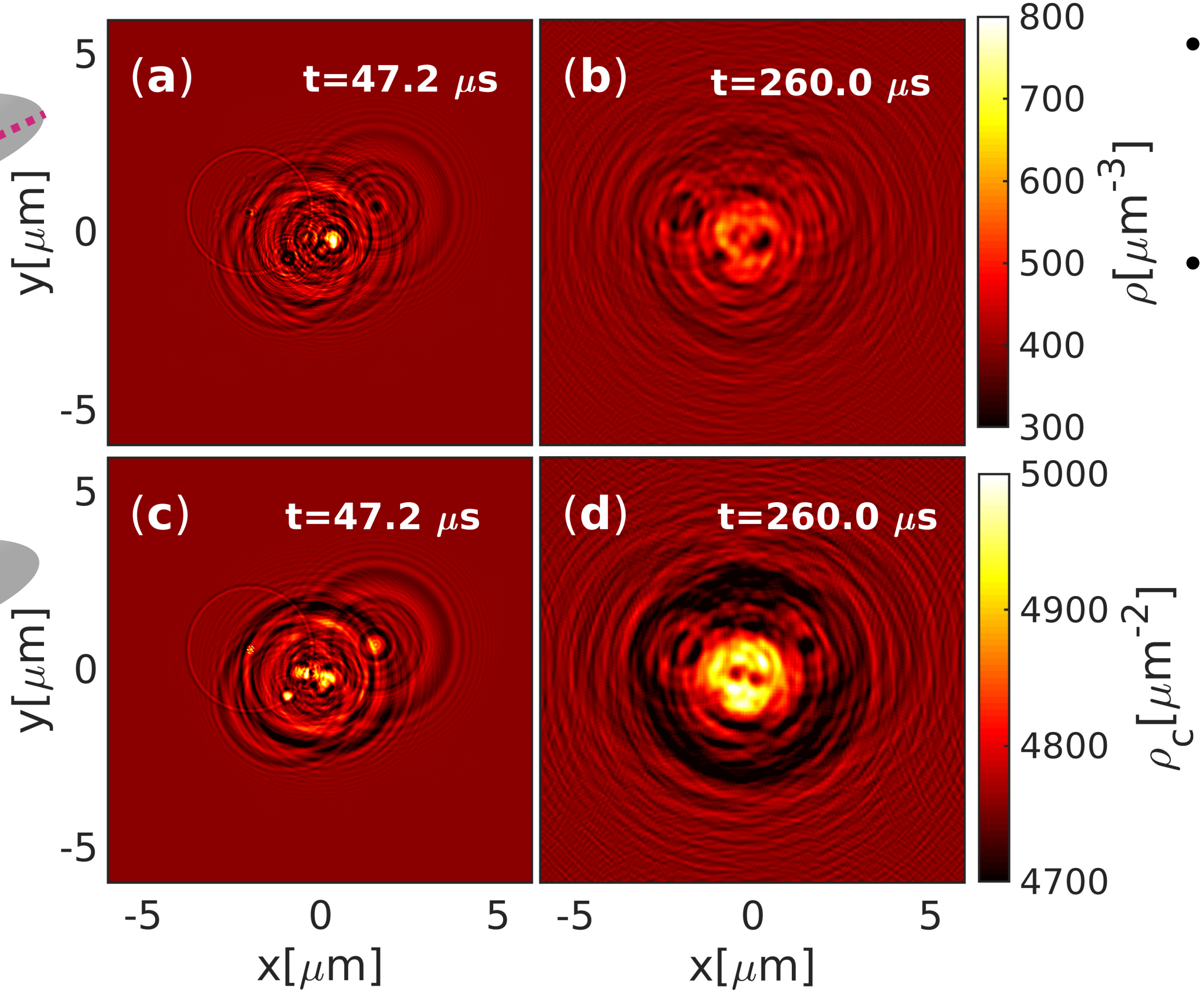
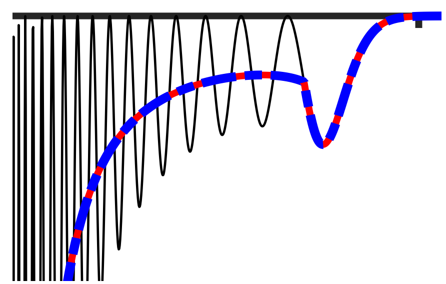






- Net attraction to focus, not seen in experiment
- Sensitivity to detailed Rydberg-BEC interactions or non-mean field dynamics?



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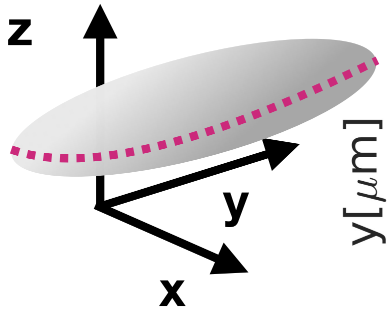
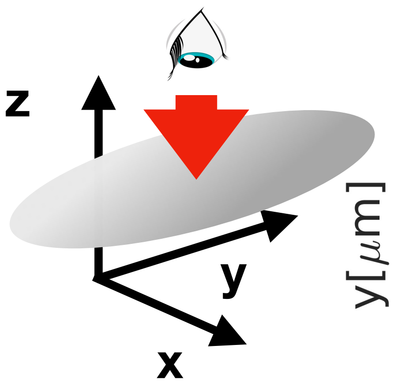
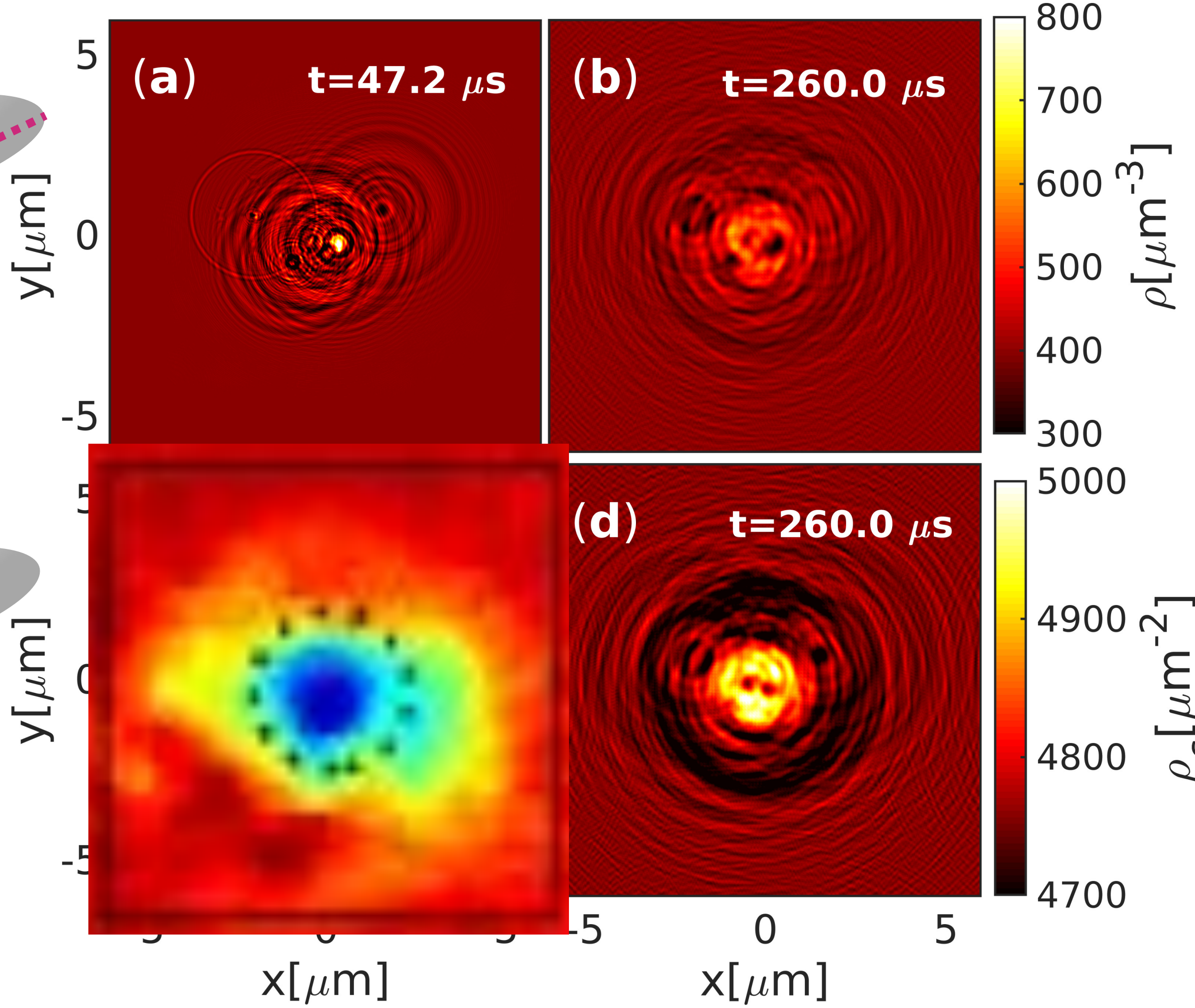
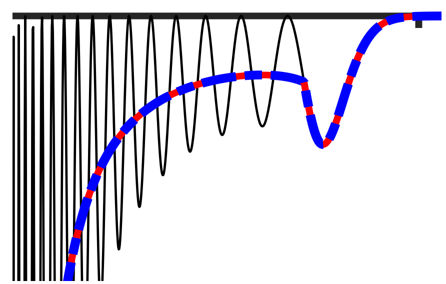
$$i\hbar\frac{\partial}{\partial t}\phi(\mathbf{R}) = \left(-\frac{\hbar^2}{2m}\nabla^2 + W(\mathbf{R}) + g\,|\phi(\mathbf{R})|^2 + \qquad V_0\,|\Psi(\mathbf{R}-\mathbf{x}_n)|^2\right)\phi(\mathbf{R})$$







- Net attraction to focus, not seen in experiment
- Sensitivity to detailed Rydberg-BEC interactions or non-mean field dynamics?

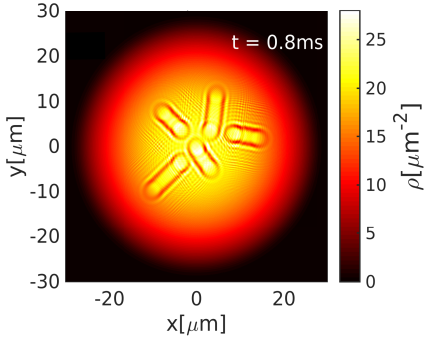


S. Tiwari *et al.*
in preparation (2021).

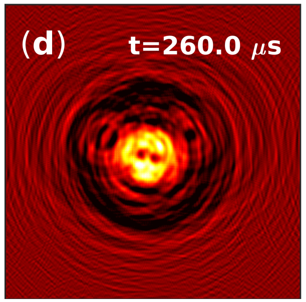
Outline

(I) Tracking of mobile Rydberg atoms in a BEC

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



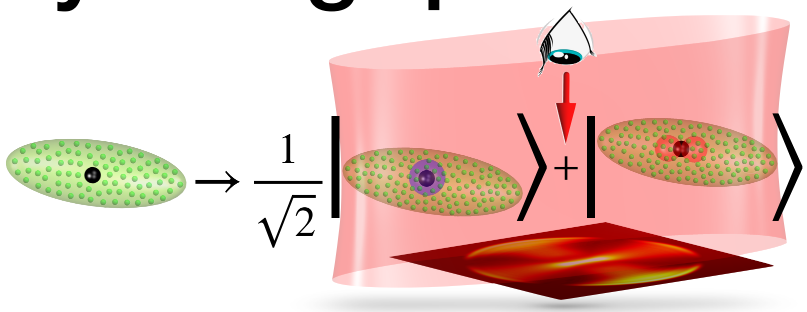
(II) BEC response to Rydberg insertion



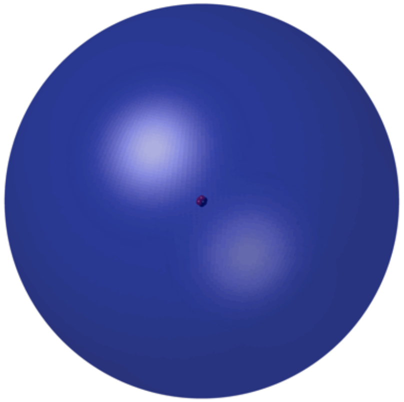
S. Tiwari *et al.* in preparation (2021).

(III) Decoherence of Rydberg qubits in a BEC

S. Rammohan *et al.*
arXiv:2011.11022 (2020).
arXiv:2006.15376 (2020).



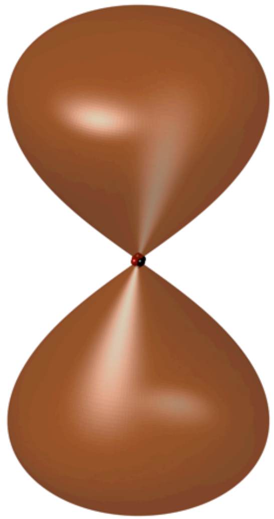
Rydberg qubit



$|\, ns \,\rangle$

n=80, l=0

$|\downarrow\rangle$

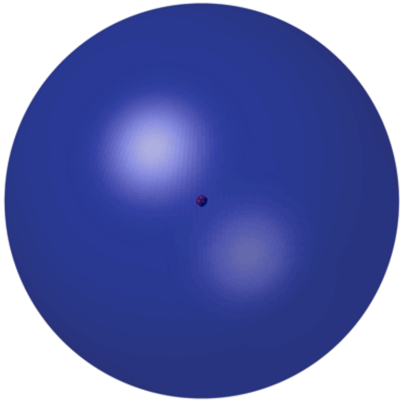


$|\, np \,\rangle$

n=80, l=1

$|\uparrow\rangle$

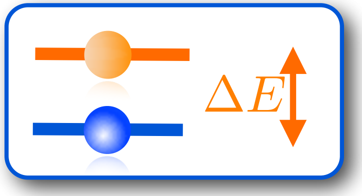
Rydberg qubit

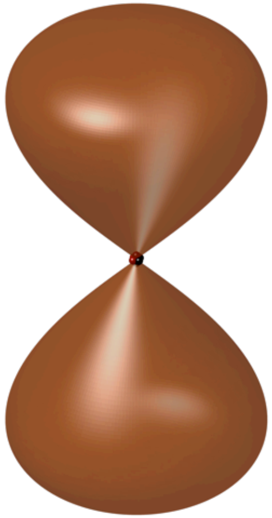


$|ns\rangle$

n=80, l=0

$|\downarrow\rangle$



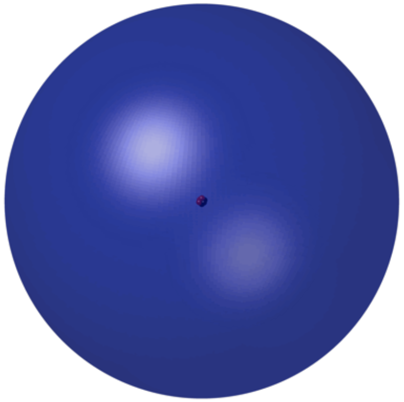


$|np\rangle$

n=80, l=1

$|\uparrow\rangle$

Rydberg qubit



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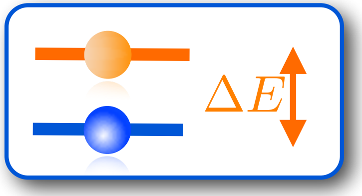
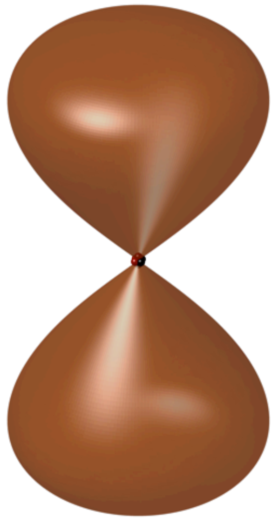
n=80, l=0

$|\downarrow\rangle$





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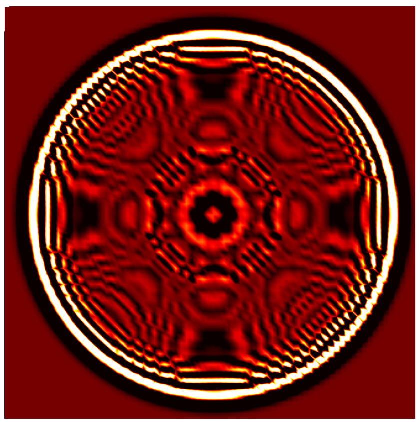
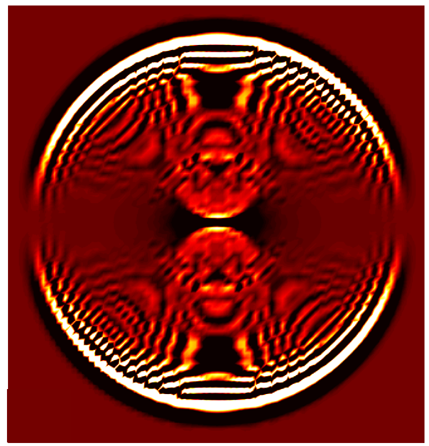
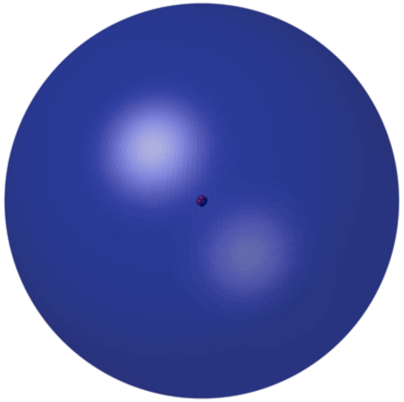


different
Imprinted
pattern

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



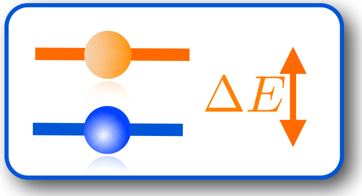
Rydberg qubit

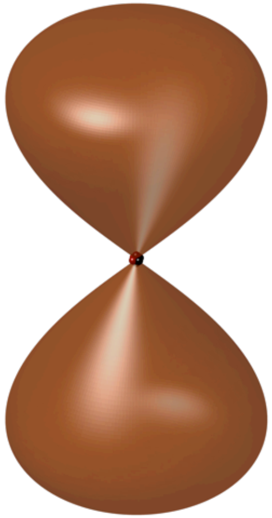


$|ns\rangle$

n=80, l=0

$|\downarrow\rangle$





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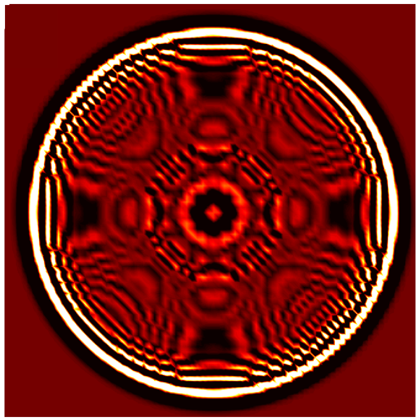

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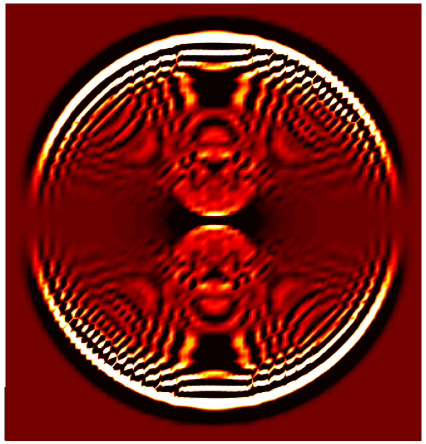
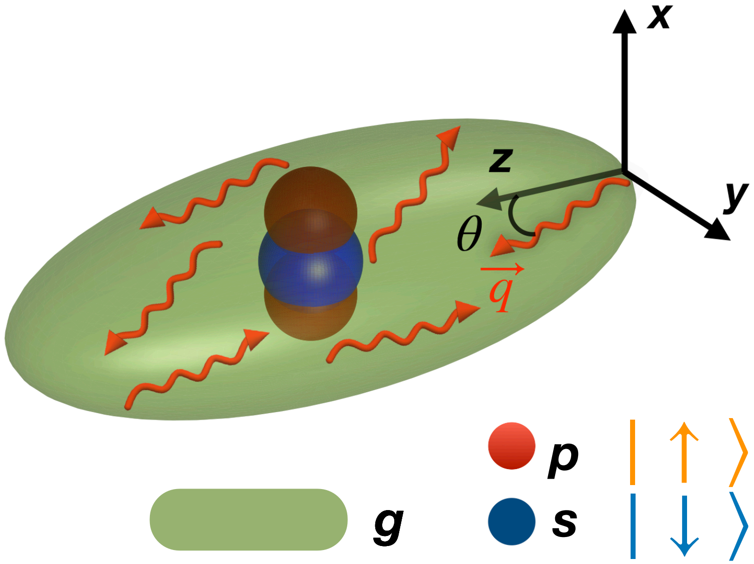


$$|\Psi\rangle = \frac{1}{\sqrt{2}}\left(|\downarrow\rangle + |\downarrow\rangle\right)?$$

- We only have **one** mean field, need to go beyond GPE?

Bogoliubov Spin-Boson model



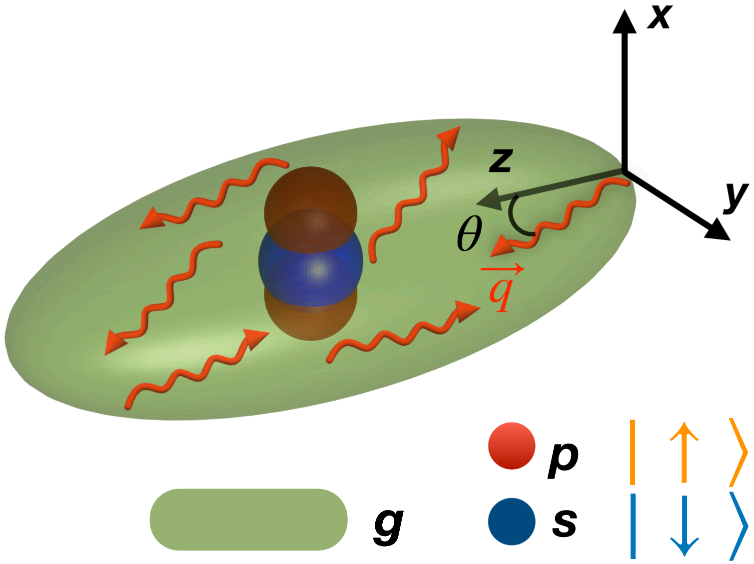
Many-body Hamiltonian

$$\hat{H} = \sum_k \int d^3\mathbf{x} \Big[\hat{\Psi}_k^\dagger(\mathbf{x}) \Big(-\frac{\hbar^2}{2m}\boldsymbol{\nabla}^2 + E_k \Big) \hat{\Psi}_k(\mathbf{x}) + \frac{1}{2}\sum_{i,j,s} \int d^3\mathbf{y}\, \hat{\Psi}_k^\dagger(\mathbf{x}) \hat{\Psi}_i^\dagger(\mathbf{y}) U_{kijs}(\mathbf{x}-\mathbf{y}) \hat{\Psi}_j(\mathbf{y}) \hat{\Psi}_s(\mathbf{x}) \Big]. \quad (1)$$

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

S. Rammohan *et al.* arXiv:2006.15376 (2020).

Bogoliubov Spin-Boson model



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

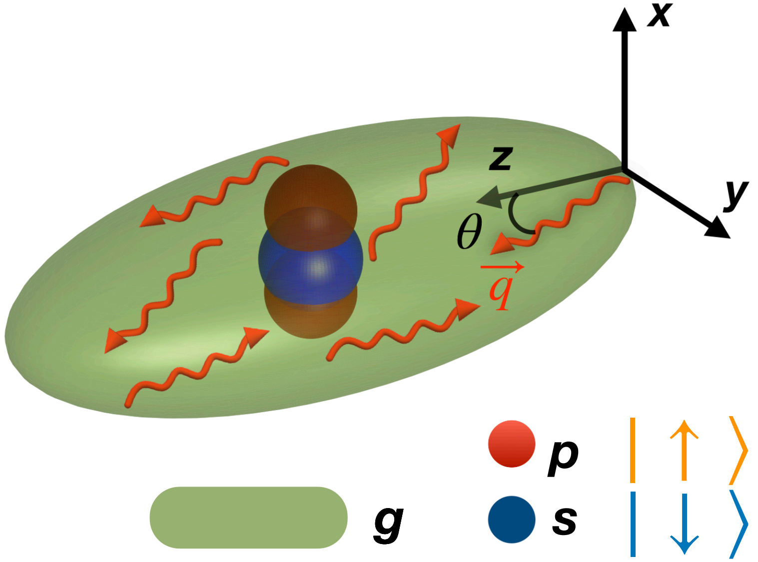
see also: Middelkamp et al. PRA **76** (2007) 022507.

Bose gas beyond mean field (Bogoliubov)

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

S. Rammohan *et al.* arXiv:2006.15376 (2020).

Bogoliubov Spin-Boson model



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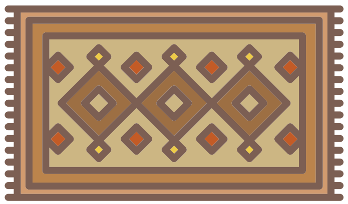
Spin-Boson Hamiltonian

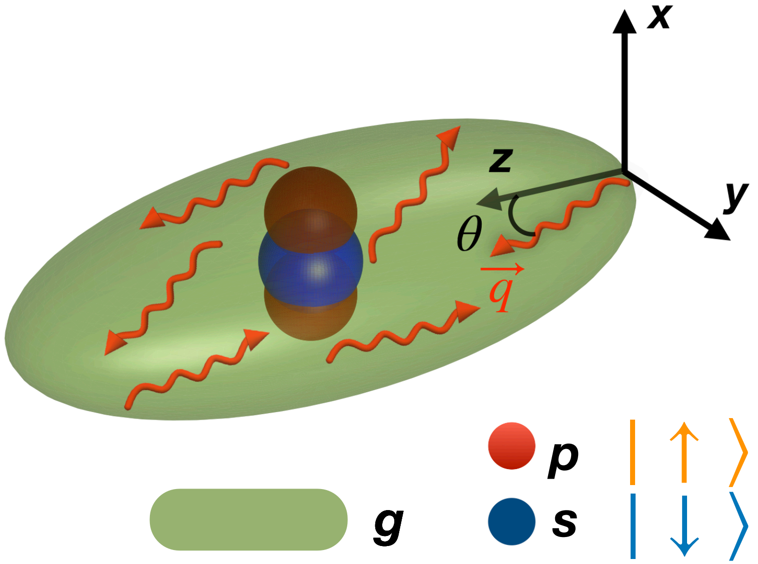
$$\hat{H}_{\rm syst} = \frac{\Delta E(t)}{2} \hat{\sigma}_z, \quad \hat{H}_{\rm env} = \sum_{\mathbf{q}} \hbar\omega_{\mathbf{q}}\, \tilde{b}_{\mathbf{q}}^\dagger \tilde{b}_{\mathbf{q}}$$

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



S. Rammohan *et al.* arXiv:2006.15376 (2020).

Bogoliubov Spin-Boson model



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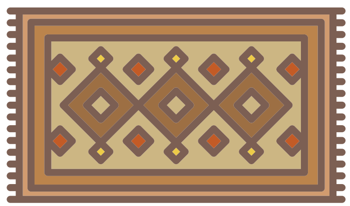


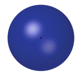
S. Rammohan *et al.* arXiv:2006.15376 (2020).

For g-impurities:
Jaksch group and Lewenstein group

GPE comparison

Spin-phonon coupling:

$$\Delta\kappa_{\mathbf{q}} = V_0\sqrt{\rho}\int d^3\mathbf{x}\left(\,|\psi^{(p)}(\mathbf{x})|^2 - |\psi^{(s)}(\mathbf{x})|^2\right)\left(u_{\mathbf{q}}e^{i\mathbf{q}x} - v^*_{\mathbf{q}}e^{-i\mathbf{q}x}\right)$$



S. Rammohan *et al.*, arXiv:2011.11022 (2020).

GPE comparison

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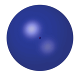

Block diagonal Hamiltonian:

$$H = \begin{bmatrix} H_\uparrow & 0 \\ 0 & H_\downarrow \end{bmatrix}$$

S. Rammohan *et al.*, arXiv:2011.11022 (2020).

GPE comparison

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Many-body wavefunction:

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

S. Rammohan *et al.*, arXiv:2011.11022 (2020).

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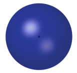

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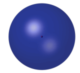

$$|\Psi_{\text{tot}}(t)\rangle = c_{\uparrow}|\uparrow\rangle \otimes |\Psi_{\uparrow}(t)\rangle + c_{\downarrow}|\downarrow\rangle \otimes |\Psi_{\downarrow}(t)\rangle$$

Spin coherence

$$\hat{\rho}_{red} = \mathbf{Tr}_{\mathscr{E}}[\,|\Psi_{tot}\rangle\langle\Psi_{tot}|\,]$$

$$\rho_{\downarrow\uparrow}(t) = c_{\downarrow}^{*}c_{\uparrow}\langle\Psi_{\uparrow}(t)|\Psi_{\downarrow}(t)\rangle$$

S. Rammohan *et al.*, arXiv:2011.11022 (2020).

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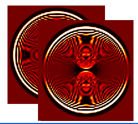
SBM

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

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

GPE



$$\Psi(\mathbf{R}_1, \cdots, \mathbf{R}_N) = \prod_k\left(\frac{\phi(\mathbf{R}_k)}{\sqrt{N}}\right)^N$$

S. Rammohan *et al.*, arXiv:2011.11022 (2020).

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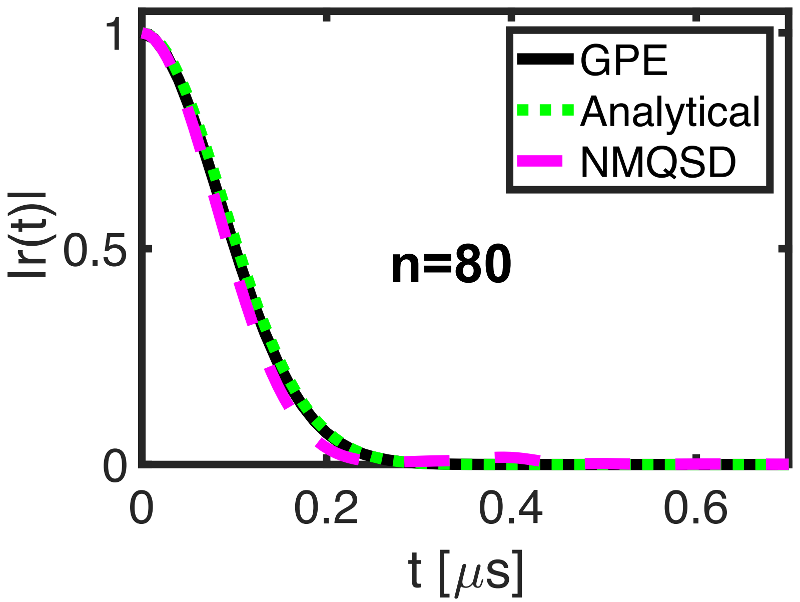
Block diagonal ... **function:**

$$H = \Big[\ldots$$

$$\ldots \otimes |\Psi_\uparrow(t)\rangle + c_\downarrow|\downarrow\rangle \otimes |\Psi_\downarrow(t)\rangle$$



Spin coherence

$$\rho_{\downarrow\uparrow}(t) = c^*_\downarrow c_\uparrow \langle \Psi_\uparrow(t) | \Psi_\downarrow(t) \rangle$$

SBM

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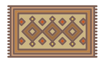
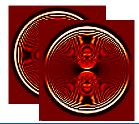


GPE



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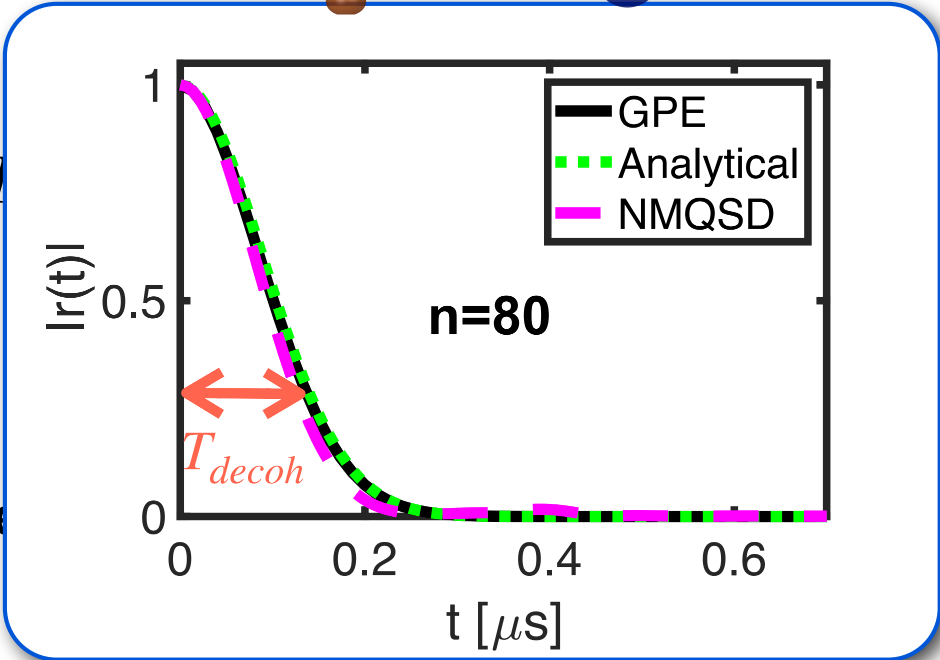

Block diagonal … **function:**

$H = [$ …

… $\otimes|\Psi_\uparrow(t)\rangle + c_\downarrow|\downarrow\rangle\otimes|\Psi_\downarrow(t)\rangle$

Spin coherence …

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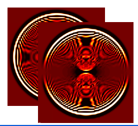
$$\rho_{\downarrow\uparrow}(t) = c^*_\downarrow c_\uparrow\langle\Psi_\uparrow(t)|\Psi_\downarrow(t)\rangle$$

GPE



Decoherence times

$T_{decoh}\approx 20$ **ns** **n=40** $\qquad T_{decoh}\approx 0.9\mu s$ **n=120**

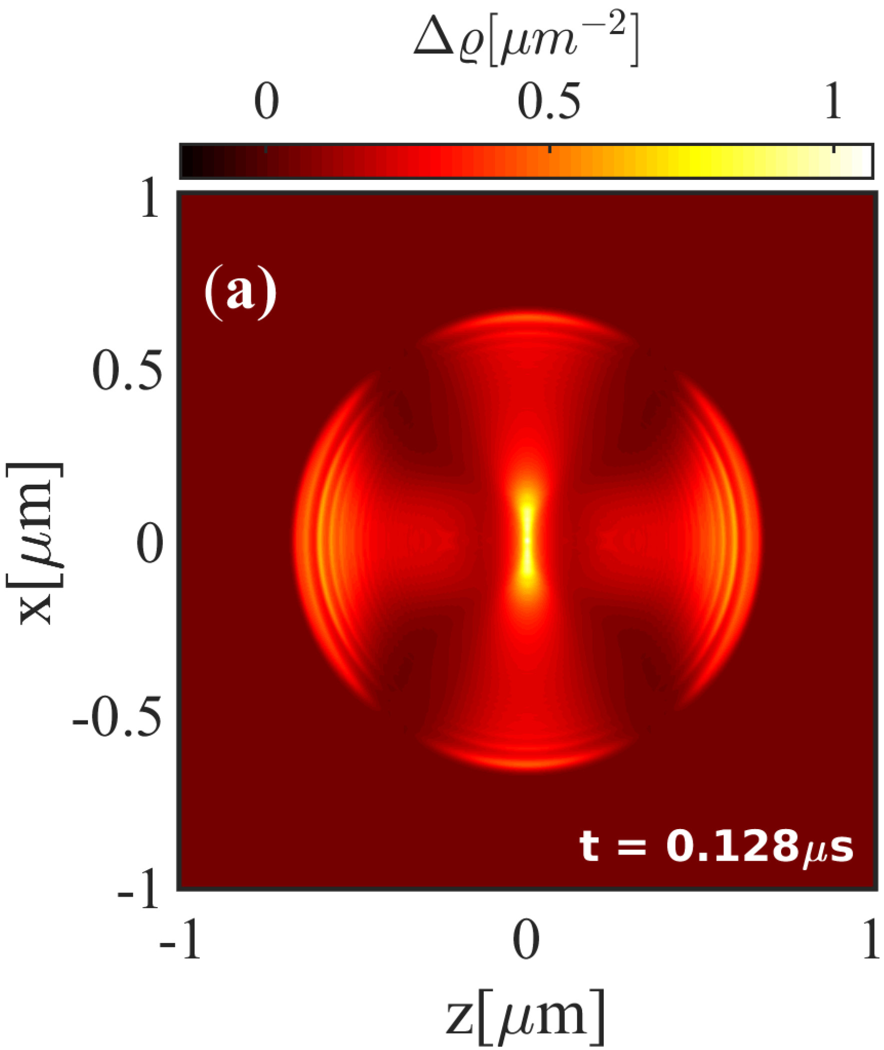
$$\Psi(\mathbf{R}_1,\cdots,\mathbf{R}_N) = \prod_k\left(\frac{\phi(\mathbf{R}_k)}{\sqrt{N}}\right)^N$$

S. Rammohan *et al.*, arXiv:2011.11022 (2020).

Imaging decohering environment

BEC column densities in

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



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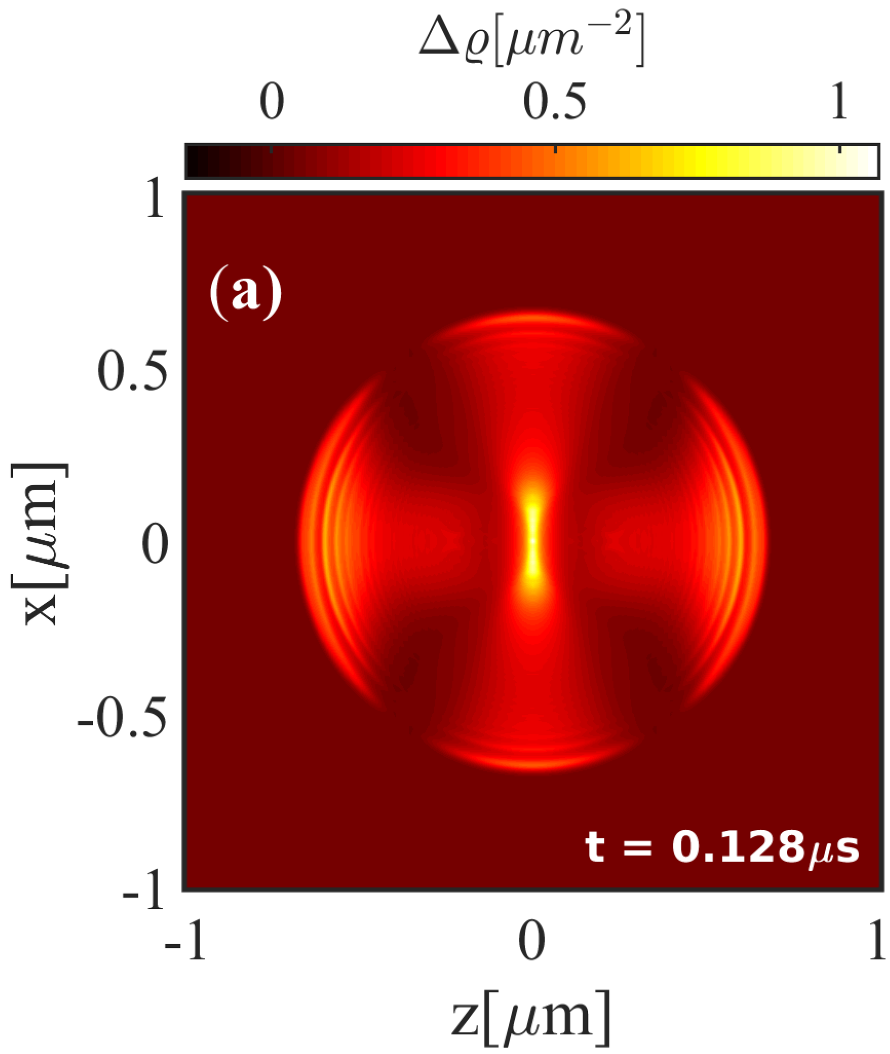
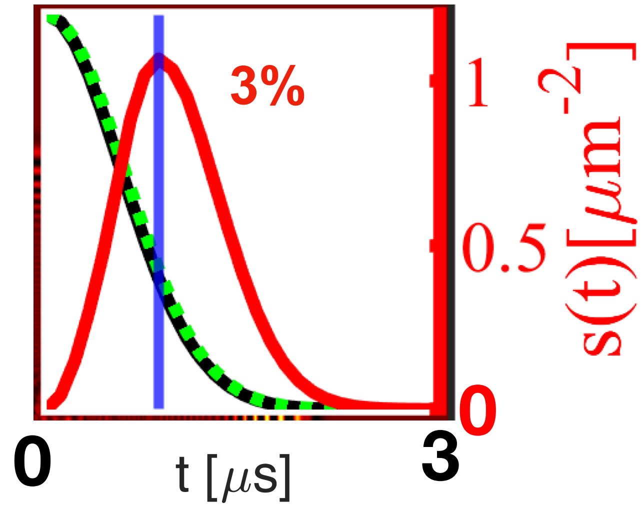




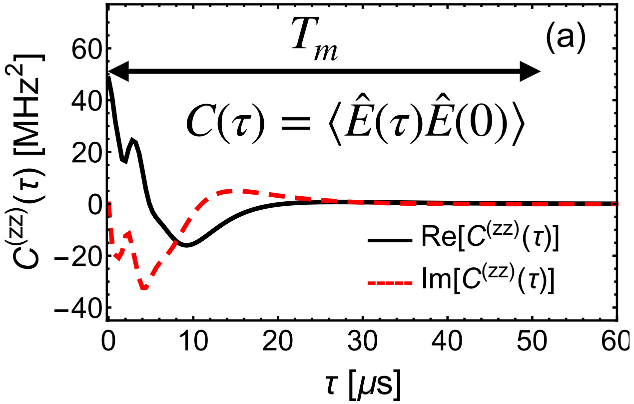
- Transient glimpse at many-body entanglement at the root of decoherence:

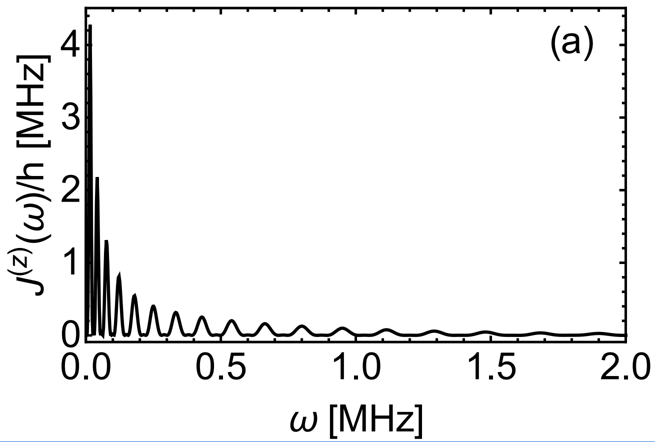
$$|\Psi_{\rm tot}(t)\rangle = c_\uparrow|\uparrow\rangle \otimes |\Psi_\uparrow(t)\rangle + c_\downarrow|\downarrow\rangle \otimes |\Psi_\downarrow(t)\rangle$$

S. Rammohan *et al.*, arXiv:2011.11022 (2020).

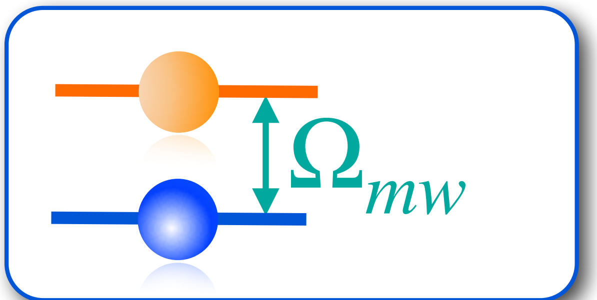
Open quantum system

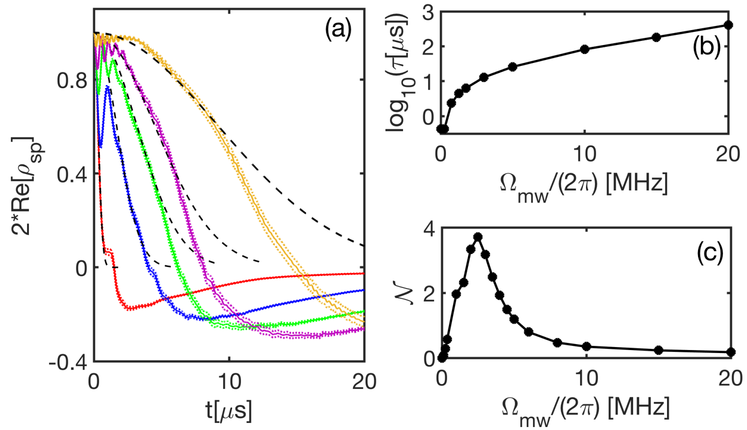
Environment (phonon) correlation functions and spectral densities





Non-Markovian Rydberg qubit dynamics





using **NMQSD:** Suess *et al.* PRL **113** (2014) 150403.

Thanks to coworkers…

Sidharth Rammohan

Shiva Kant Tiwari

Abhijit Pendse

Aritra Mishra

Anil Kumar

Rejish Nath

Alexander Eisfeld

…collaborators…

Felix Engel, Florian Meinert, Marcel Wagner, Richard Schmidt

…and funding:

MAX-PLANCK-GESELLSCHAFT

SERB INDIA

Thanks to current group

Post-Doc:

Aniruddha Mitra
Ajith Ramachandran
Abhijit Pendse

PhD:

Shivakant Tivari
Sidharth Rammohan

MAX-PLANCK-GESELLSCHAFT

Thanks to current group

INDIAN INSTITUTE OF SCIENCE EDUCATION AND RESEARCH BHOPAL

Yash Palan
Swayangdipta Bera
Neethu Abraham

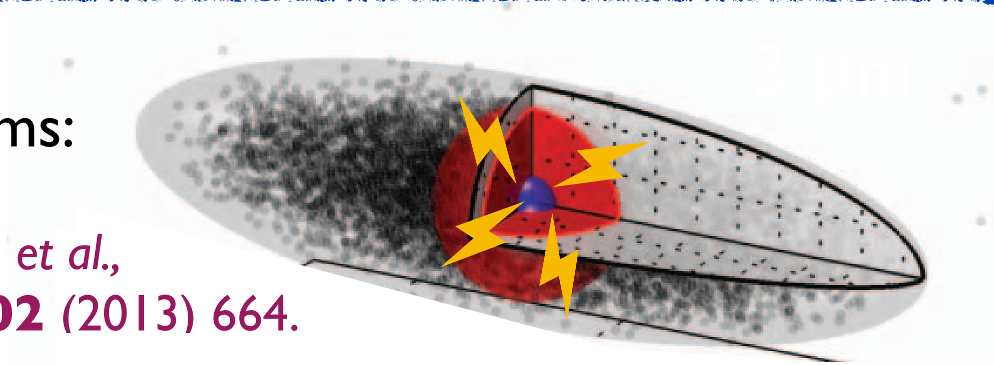
MSc:
(2019-2020)
Aritra Mishra
K Sridevi
Siddhartha Poddar

Post-MSc:
Sakshi Bahamnia

Summary

- Combination of two extreme systems: Rydberg atoms and BEC:

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



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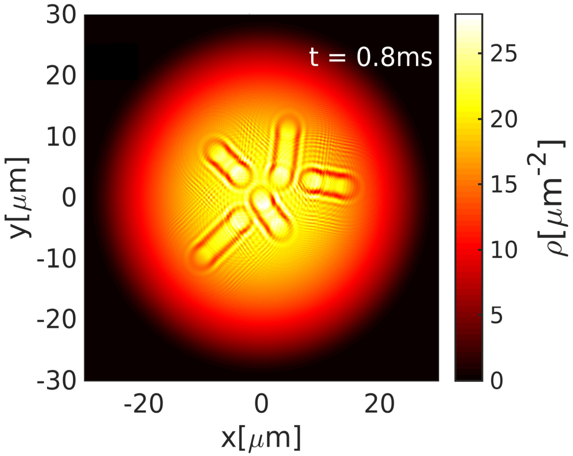
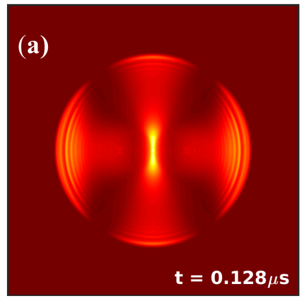
S. Tiwari and S. Wüster,
PRA **99** 043616 (2019)

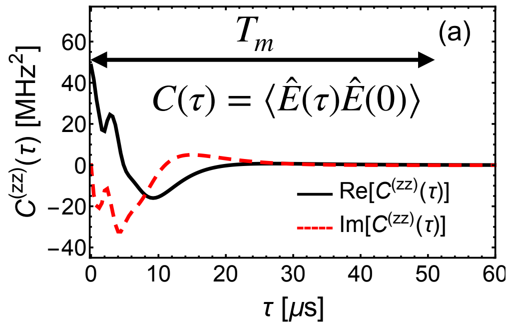


- Imaging the decohering interface

S. Rammohan *et al.*
arXiv:2011.11022 (2020).
arXiv:2006.15376 (2020).



- Tunable open quantum system



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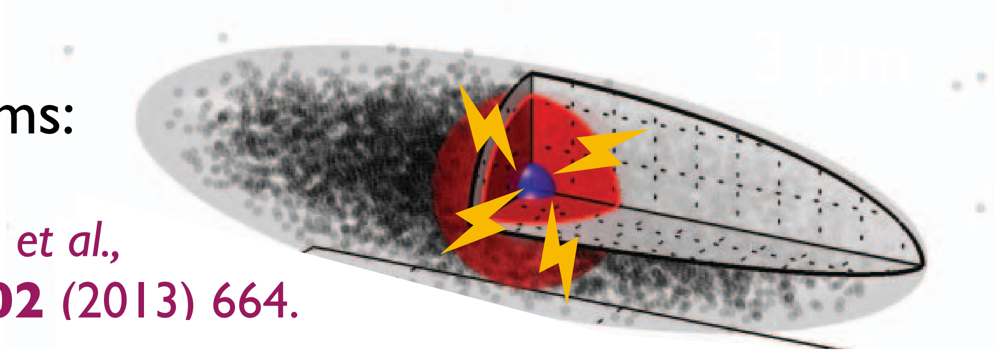

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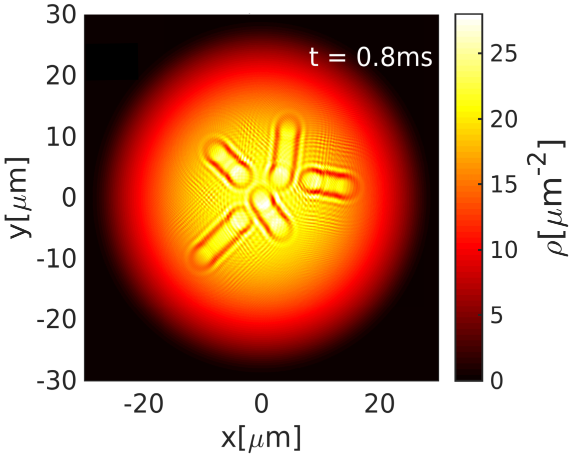

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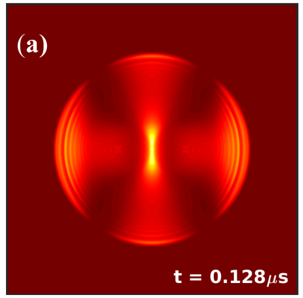

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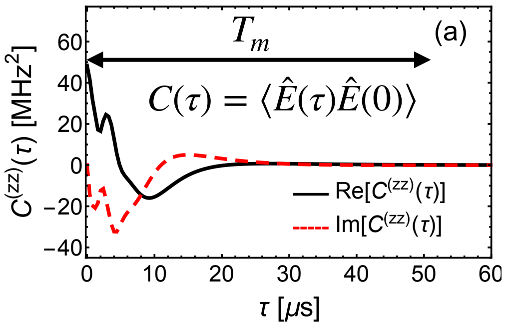
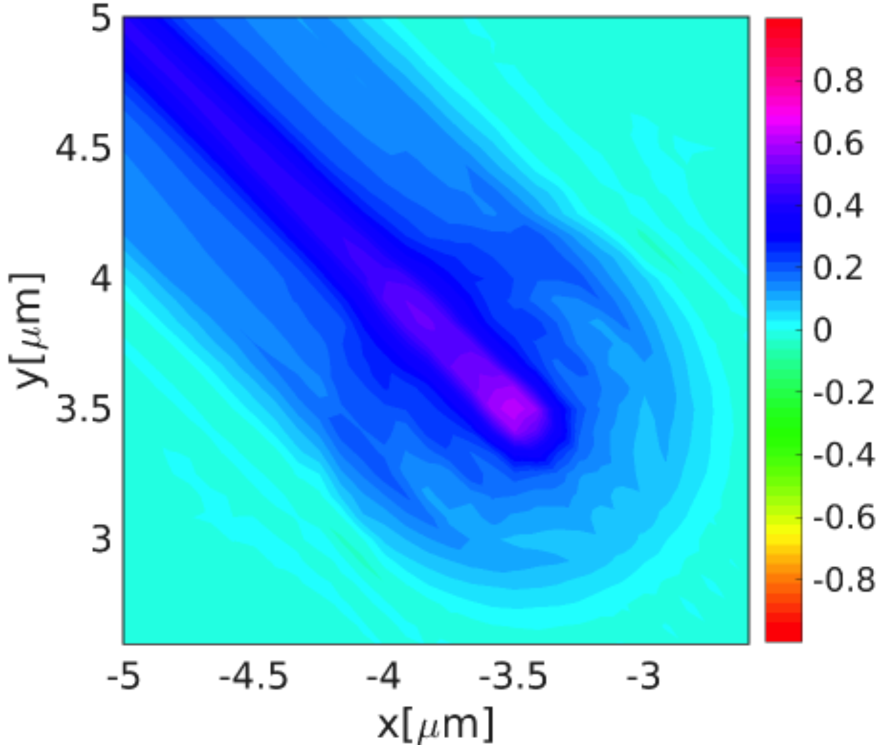
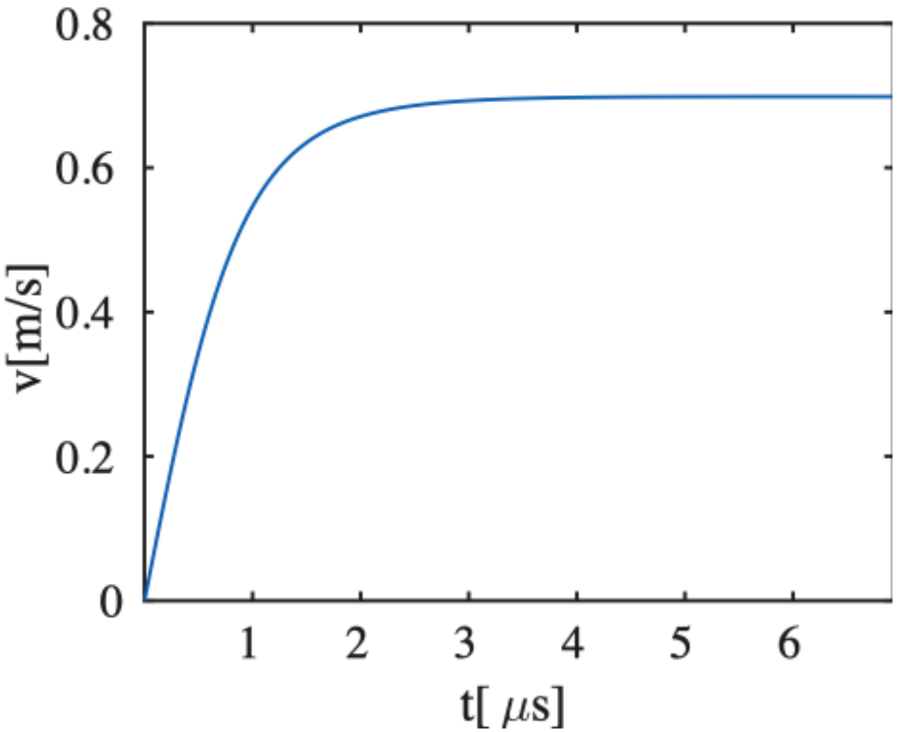


Thanks for your attention

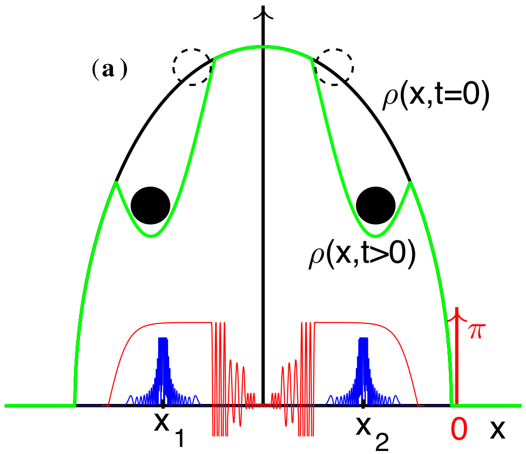
Appendix

Velocity dependence



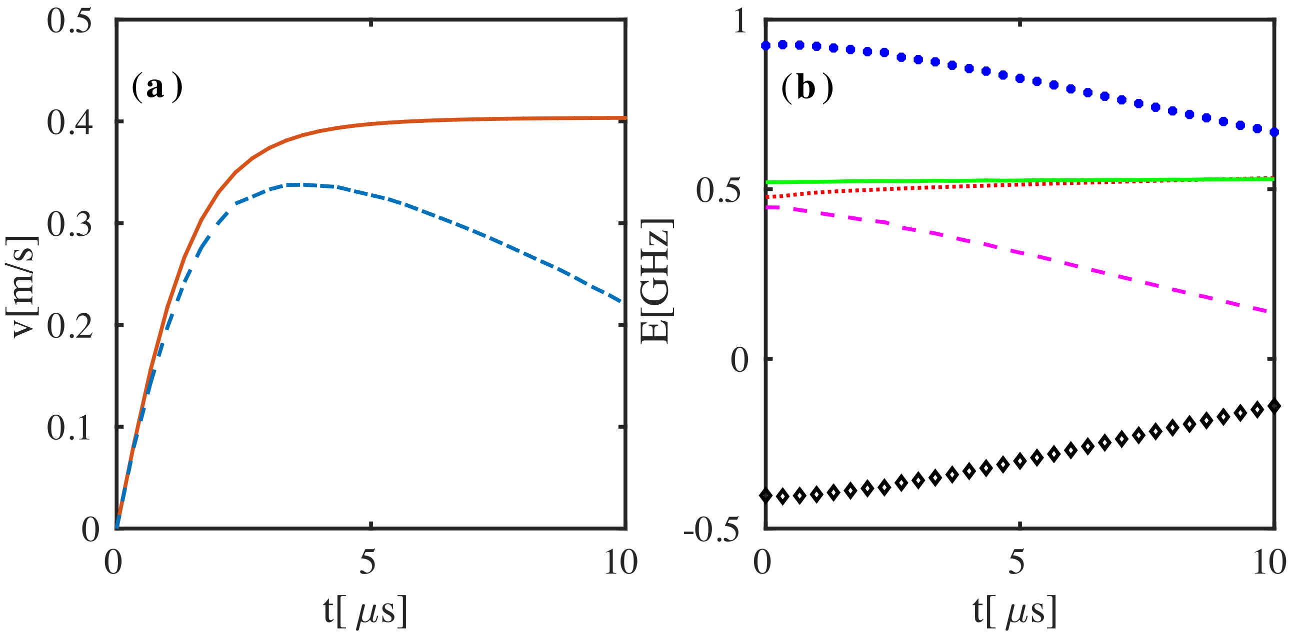


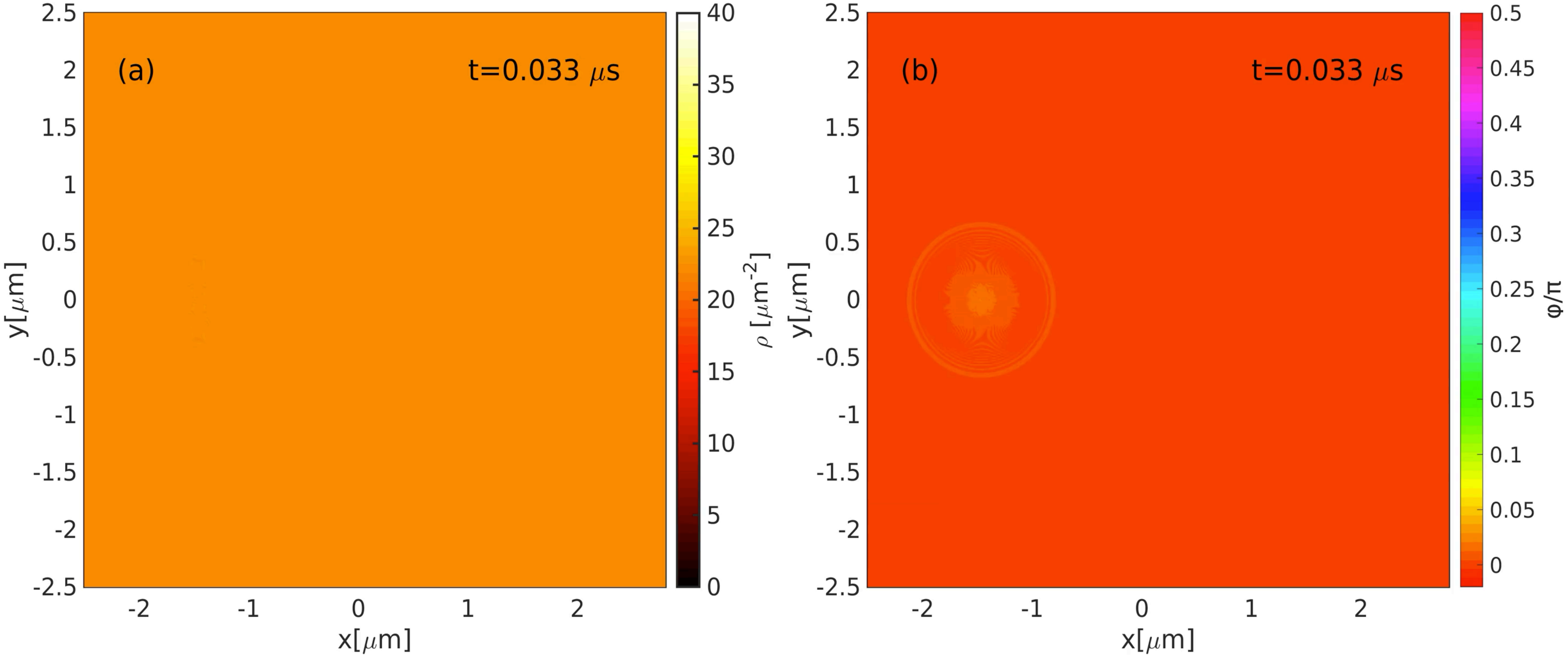
Condensate backaction



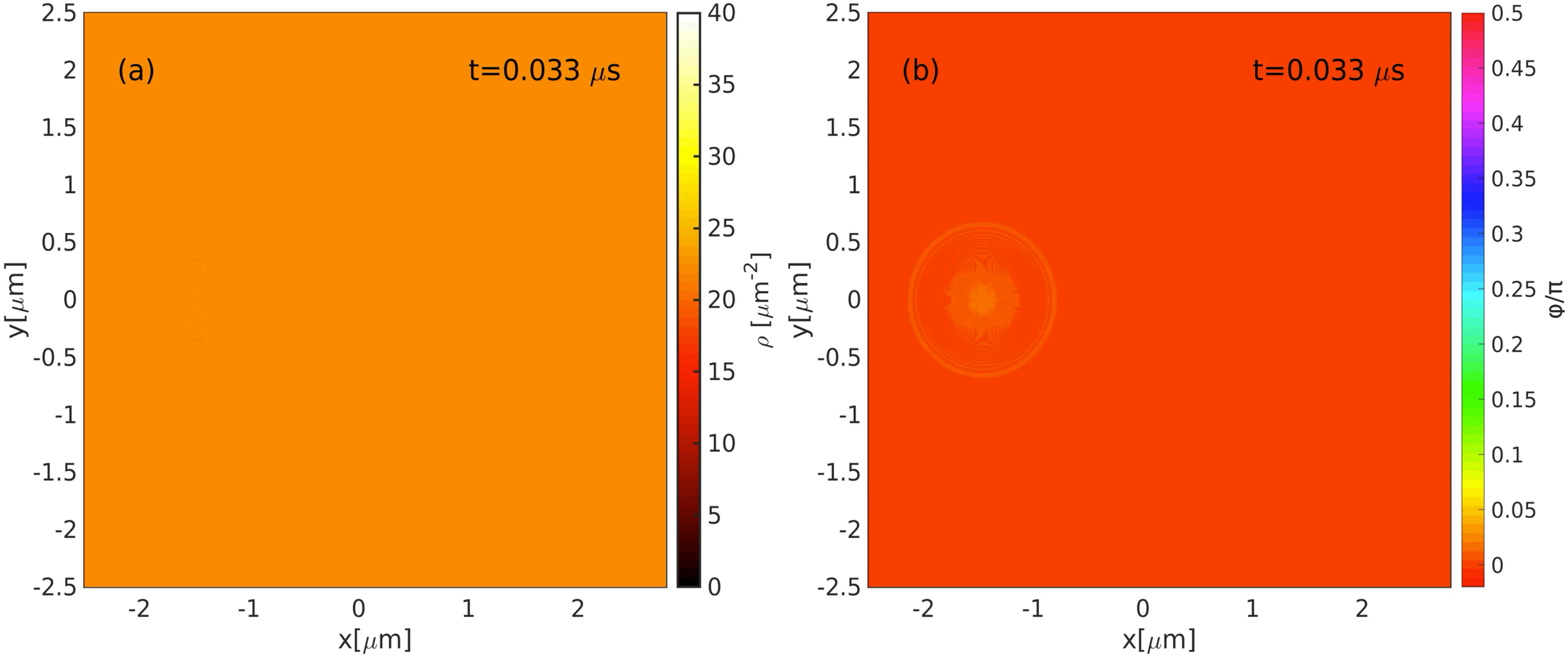
$$m\frac{\partial^2}{\partial t^2}\mathbf{x}_n = -\nabla_{\mathbf{x_n}}\left[V_{RR}(\mathbf{X}) + \bar{V}(\mathbf{x}_n)\right]$$

$$\bar{V}(\mathbf{x}_n) = \int d^2\mathbf{R}\; V_0|\Psi(\mathbf{R}-\mathbf{x}_n)|^2|\phi(\mathbf{R})|^2$$

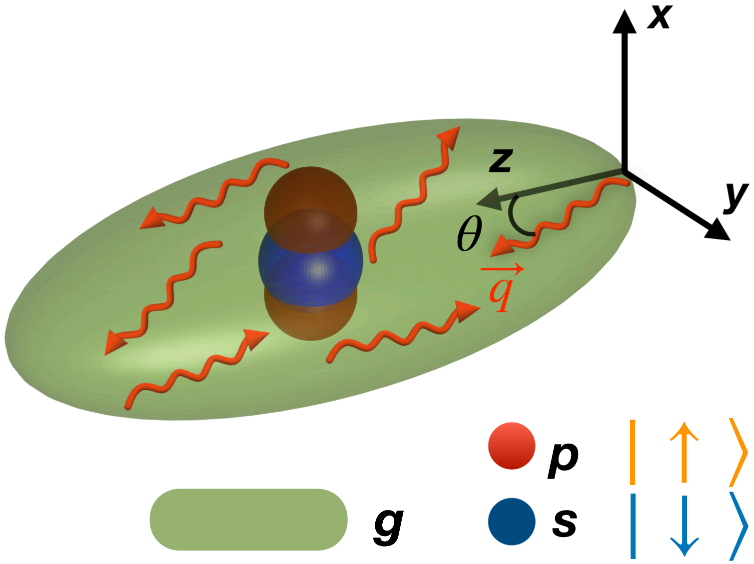




(a)
t=0.033 μs
y[μm]
x[μm]
ρ [μm⁻²]
(b)
t=0.033 μs
y[μm]
x[μm]
φ/π


(a)
t=0.033 μs
y[μm]
x[μm]
ρ [μm^-2]
(b)
t=0.033 μs
y[μm]
x[μm]
φ/π

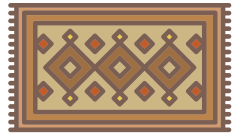
Open quantum system

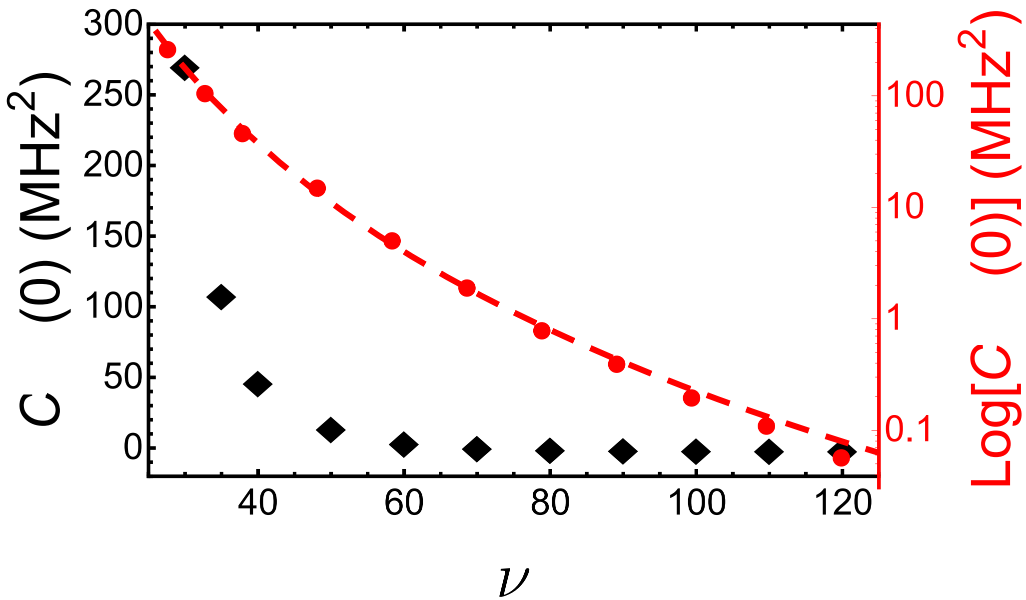


Spin-Boson Hamiltonian

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

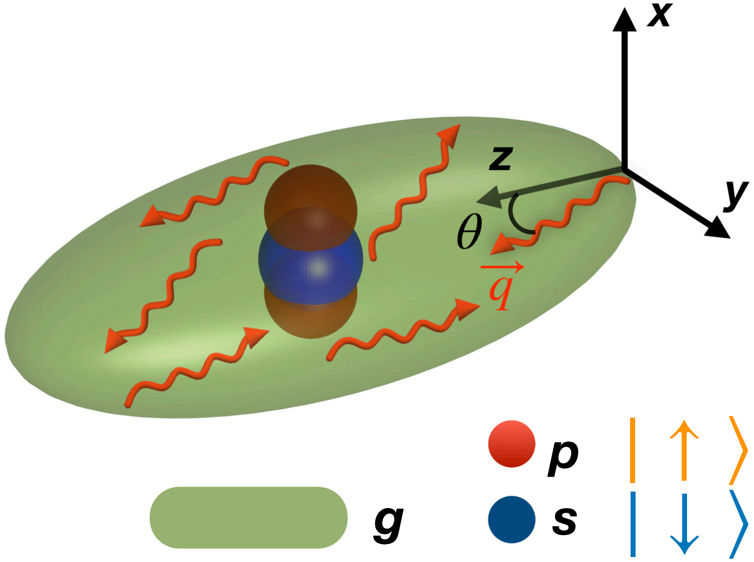
$$\hat{H}_{\text{int}} = \sum_{\mathbf{q}} \frac{\Delta\kappa_{\mathbf{q}}}{2}\left(\tilde{b}_{\mathbf{q}} + \tilde{b}^{\dagger}_{\mathbf{q}}\right)\hat{\sigma}_z. \quad +$$





S. Rammohan *et al.* arXiv:2006.15376 (2020).

Open quantum system



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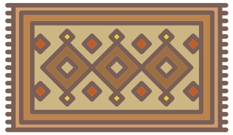
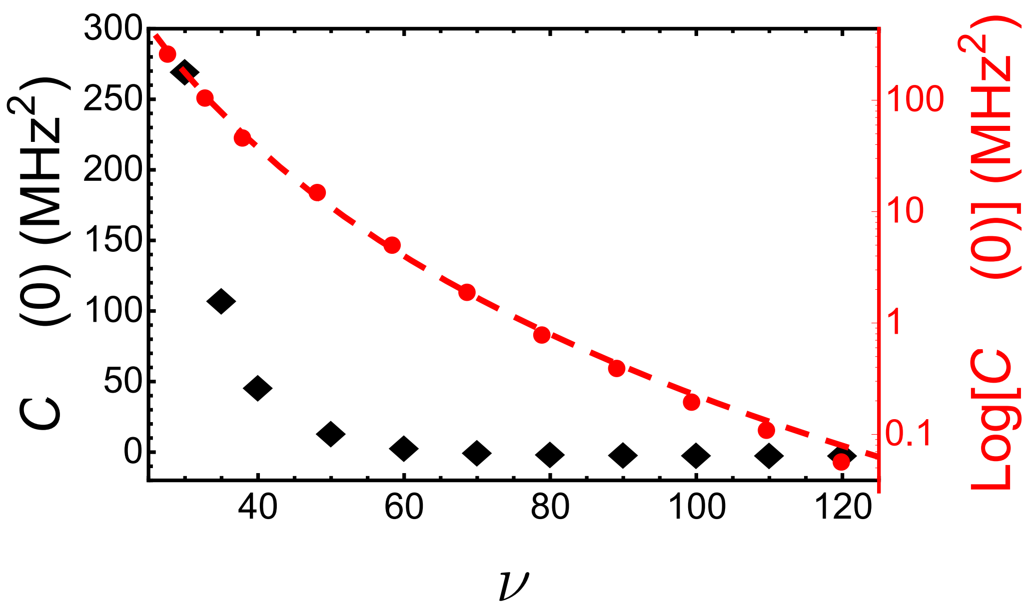
S

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

S +





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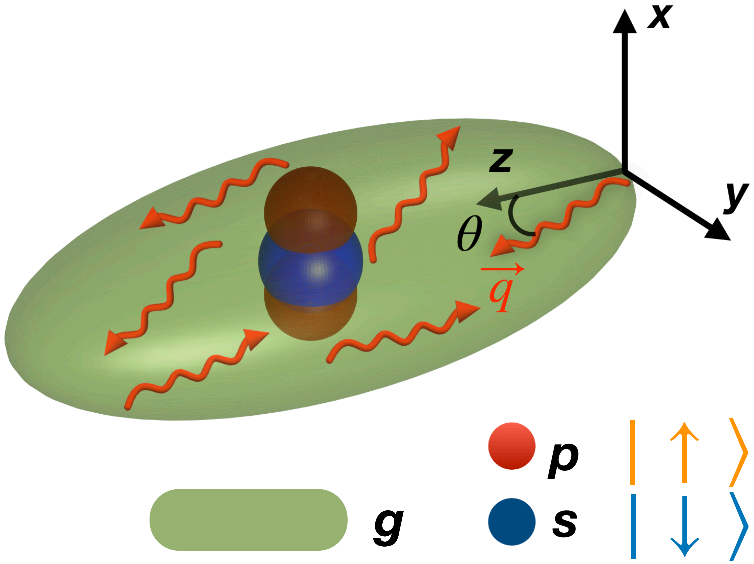

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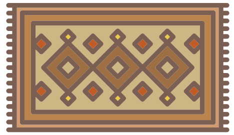
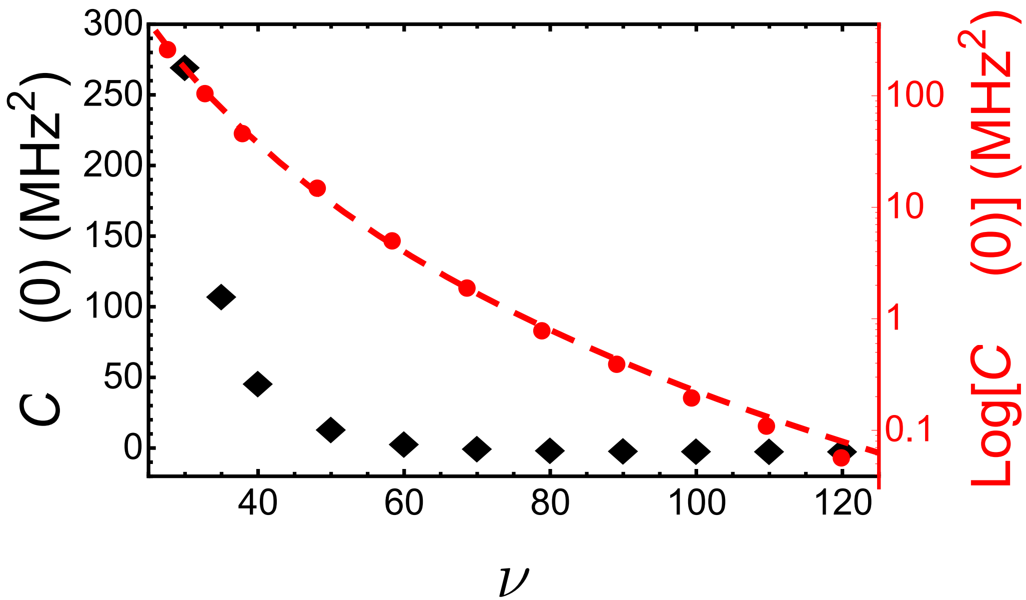
E S +





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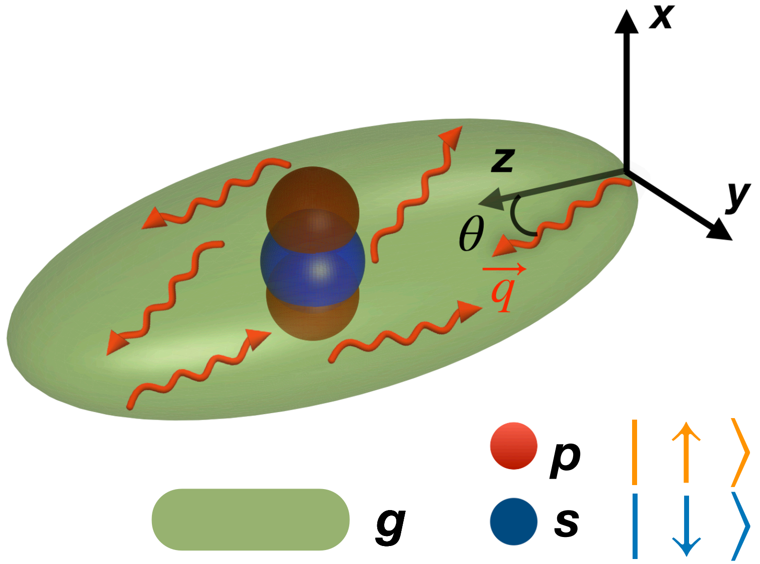

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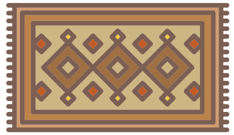
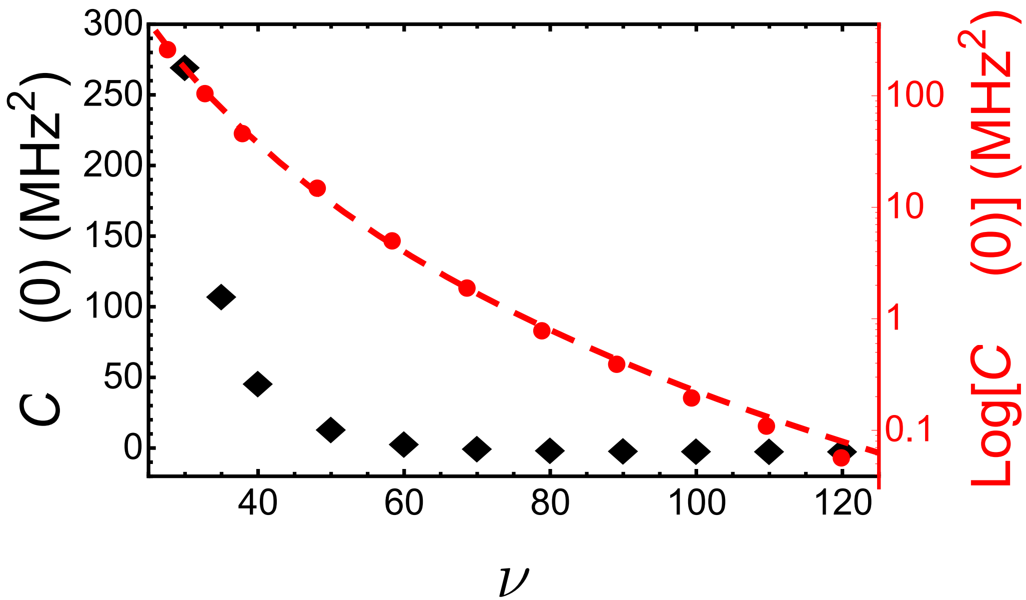


$$\hat{H}_{int} = \hat{E} \otimes \hat{S}$$



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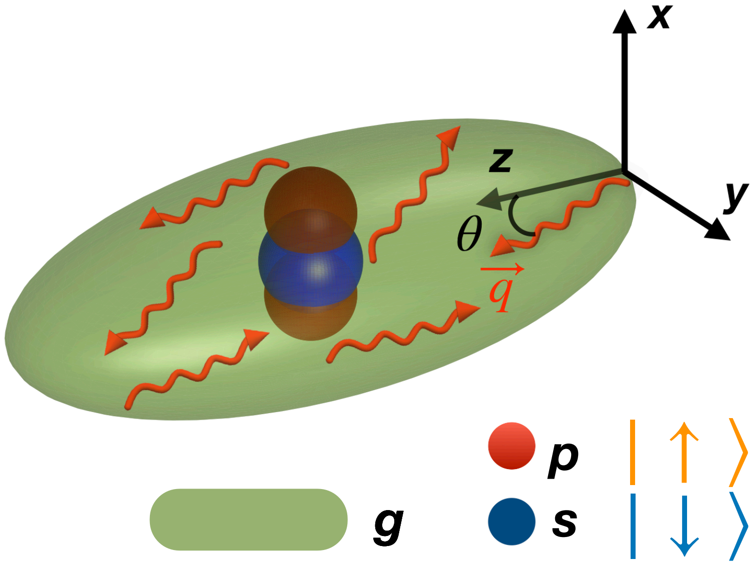

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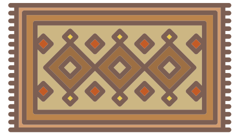
E S +



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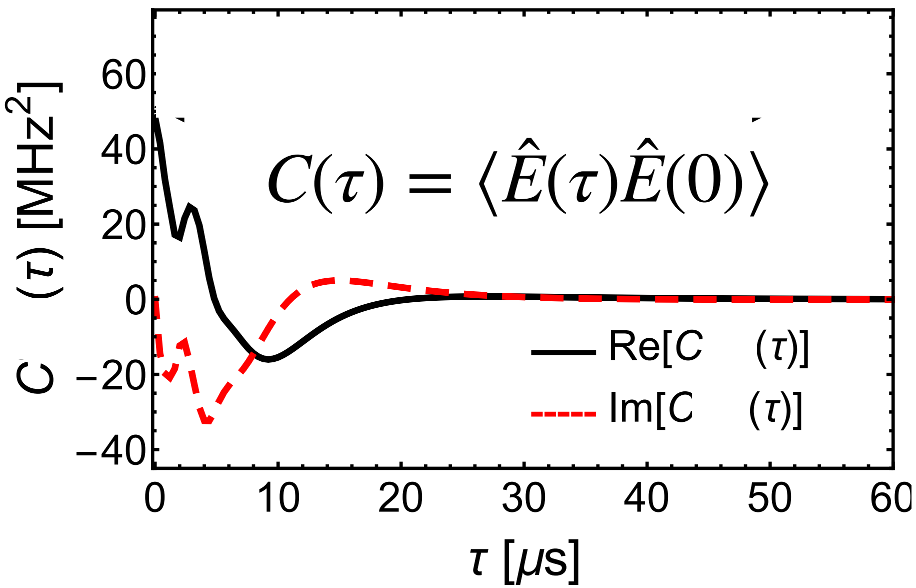

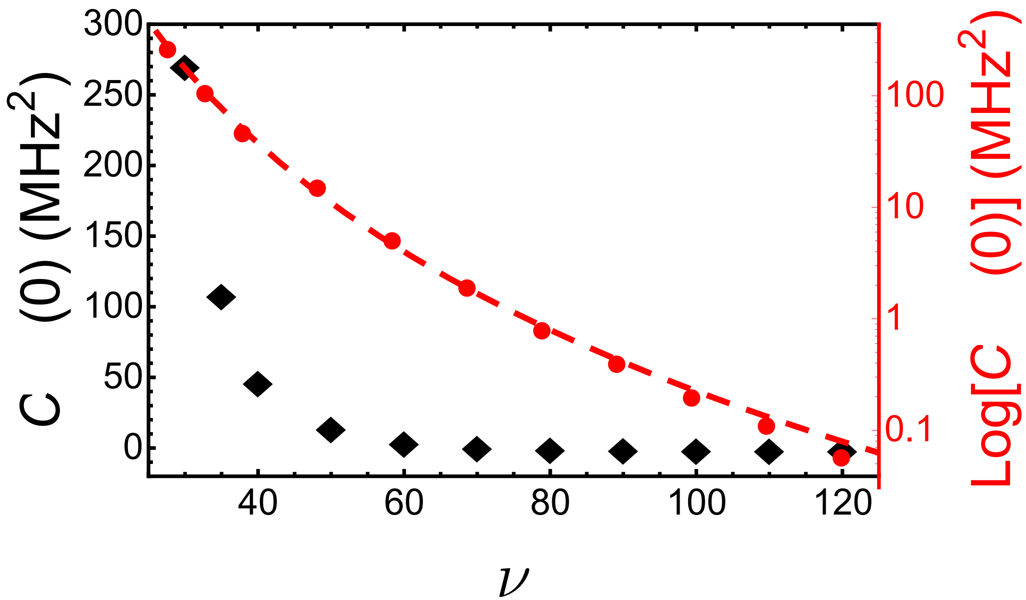

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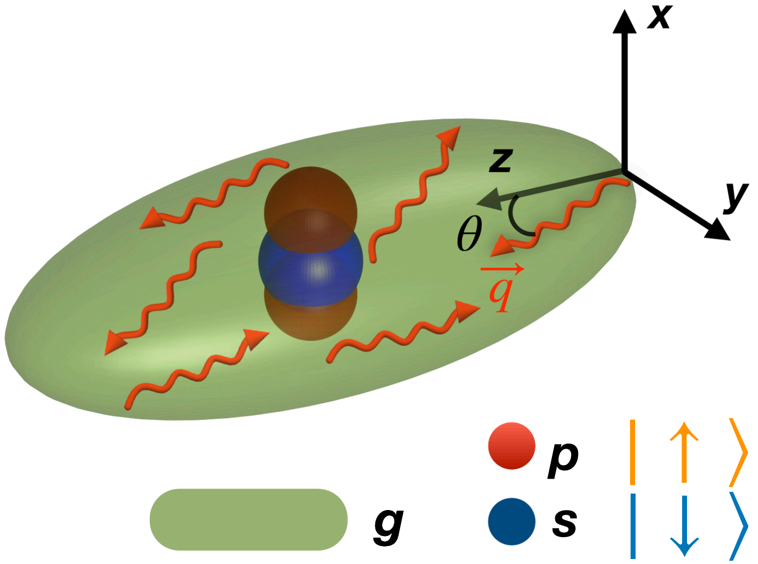

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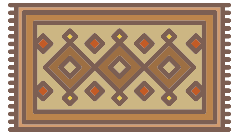

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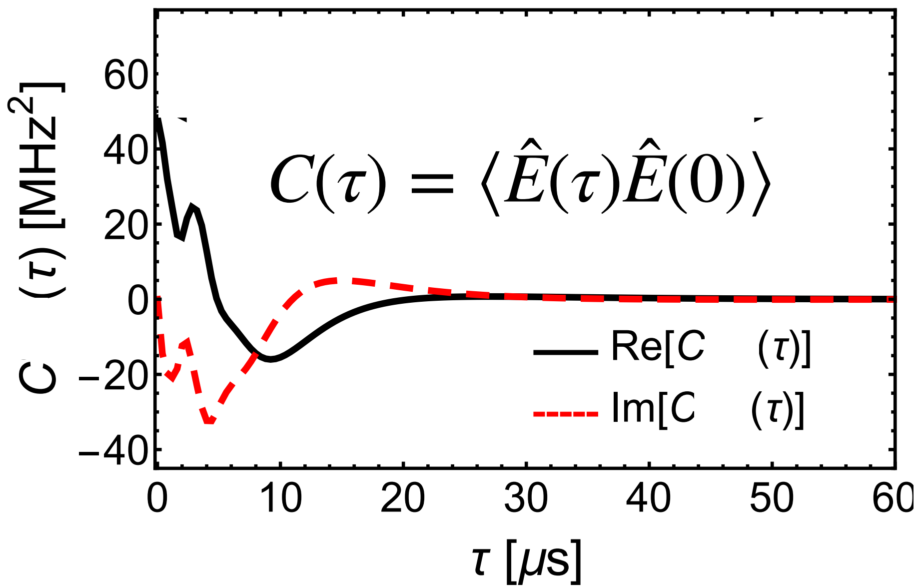
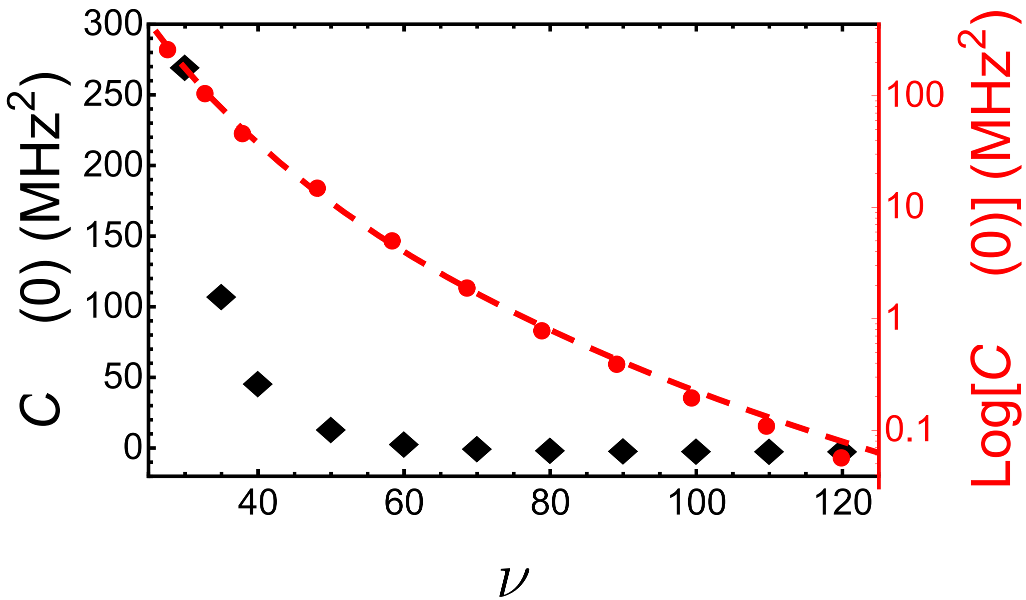
$$T_{decoh} \approx 1/\sqrt{2C(0)}$$





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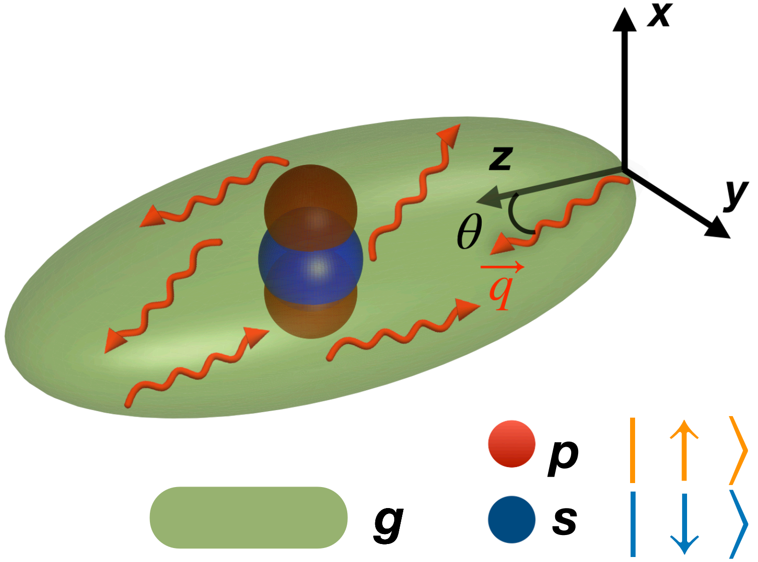

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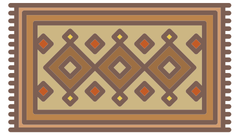

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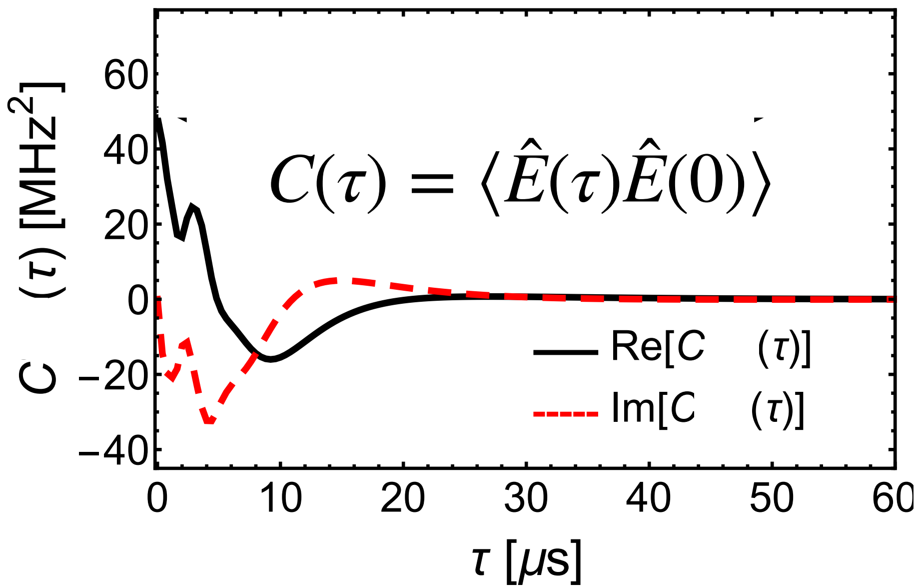

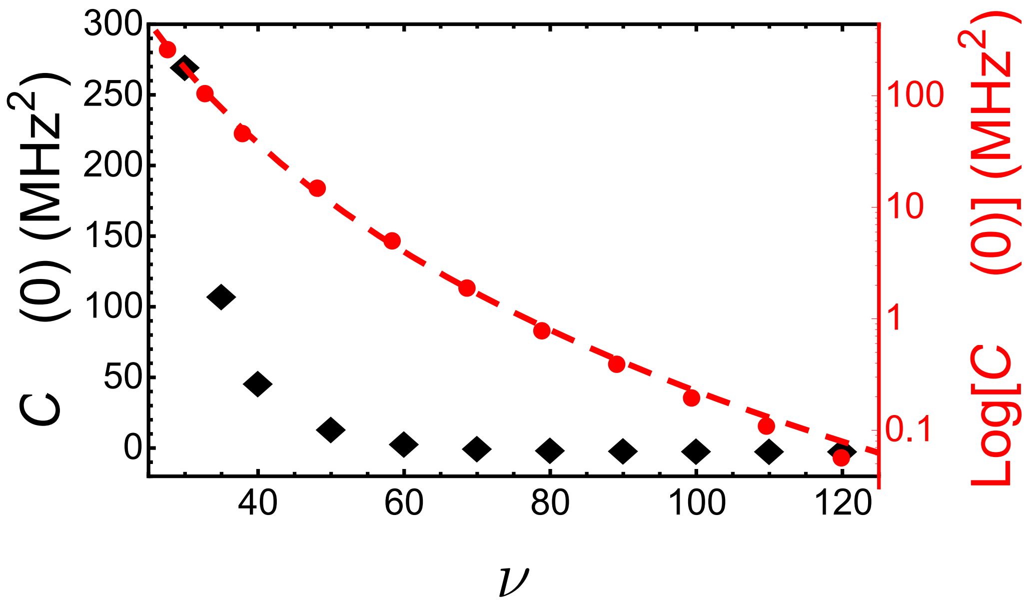

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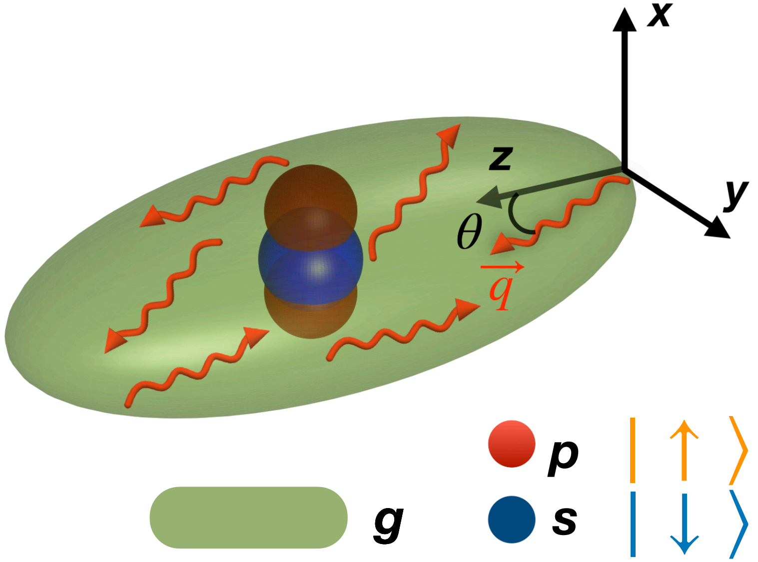

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S E

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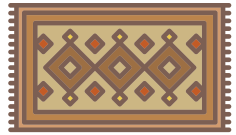
E S +



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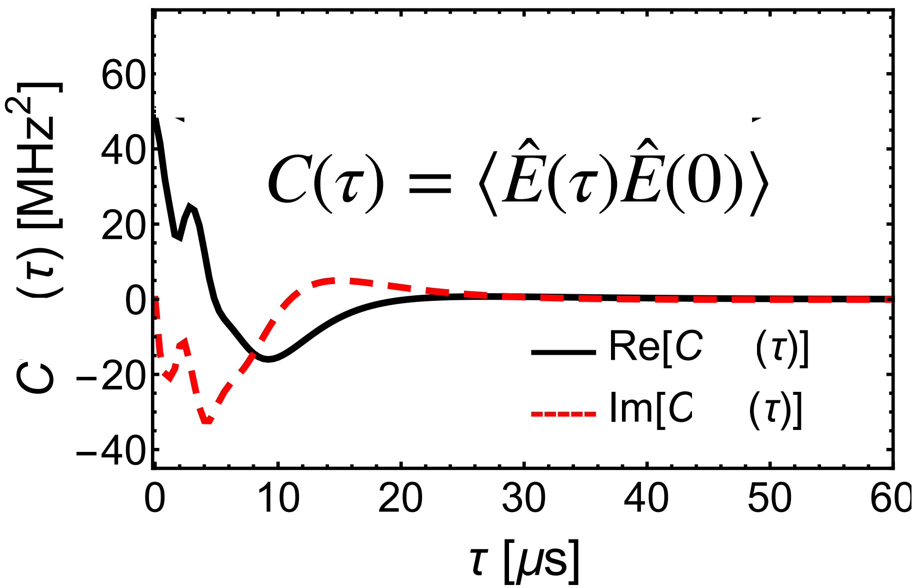
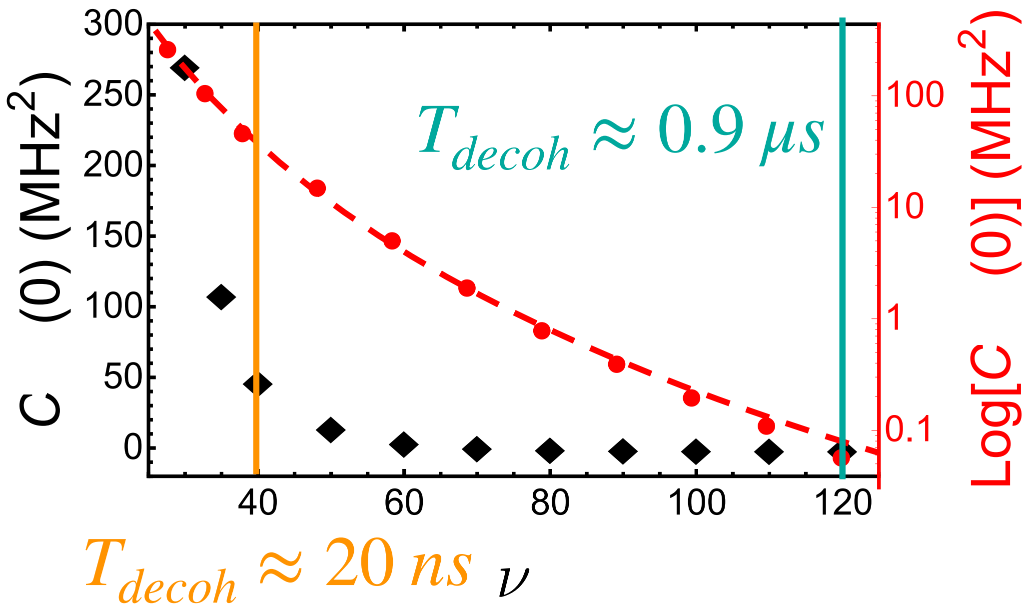




$T_{decoh} \approx 20\ ns$

S. Rammohan *et al.* arXiv:2006.15376 (2020).

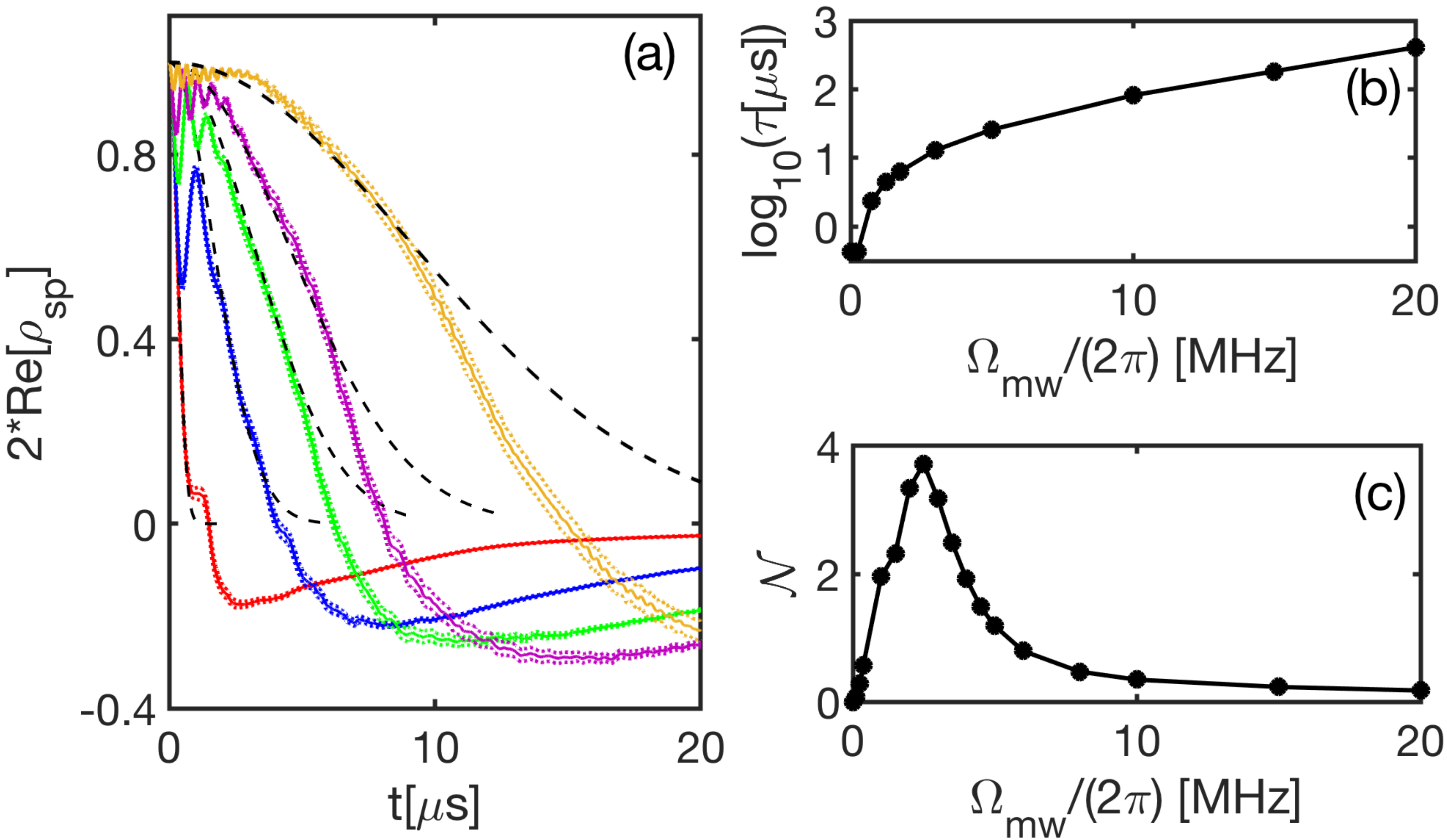
Full Spin-Boson Model

$$\epsilon_q = \hbar\omega_q = \sqrt{\frac{\hbar^2 q^2}{2m}\left(\frac{\hbar^2 q^2}{2m} + 2U_0\rho\right)}$$

$$\hat{H}_{\text{tot}} = \hat{H}'_{\text{syst}} + \sum_{\mathbf{q}} \hbar\omega_q \, \tilde{b}^\dagger_{\mathbf{q}} \tilde{b}_{\mathbf{q}} + \sum_{\mathbf{q}} \frac{\Delta\kappa_{\mathbf{q}}}{2} \left(\tilde{b}_{\mathbf{q}} + \tilde{b}^\dagger_{\mathbf{q}}\right) \hat{\sigma}_z + i \sum_{\mathbf{q}} \kappa^{(sp)}_{\mathbf{q}} \left(\tilde{b}_{\mathbf{q}} - \tilde{b}^\dagger_{\mathbf{q}}\right) \hat{\sigma}_y + const, \tag{21}$$

$$\hat{H}'_{\text{syst}} = \left[\frac{\Delta E}{2} + \sum_{\mathbf{q}} \frac{\Delta\kappa_{\mathbf{q}} \, \bar{\kappa}_{\mathbf{q}}}{2\hbar\omega_q} \left(\cos(\omega_q t) - 1\right)\right] \hat{\sigma}_z$$

Non-Markovian Rydberg qubit dynamics



NMQSD

$$\frac{\partial}{\partial t} f^{(\mathbf{k})}(t) = \bigg(-i\hat{H}_{\rm syst} - \mathbf{k}\cdot\mathbf{w} + \hat{L}\tilde{z}_t \bigg) f^{(\mathbf{k})}(t)$$

$$+ \sum_j k_j g_j f^{(\mathbf{k}-\mathbf{e}_j)}(t) - \sum_j (\hat{L}^\dagger - \langle \hat{L}^\dagger \rangle) f^{(\mathbf{k}+\mathbf{e}_j)}(t)$$

$$\overline{z_t z_s^*} = C(t-s)$$

$$\tilde{z}_t = z_t^* + \int_0^t ds \;\; C^*(t-s)\langle \hat{L}^\dagger \rangle$$