Quantum Gas Microscopes II

Long-Range Interacting Many-Body Systems

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Overview

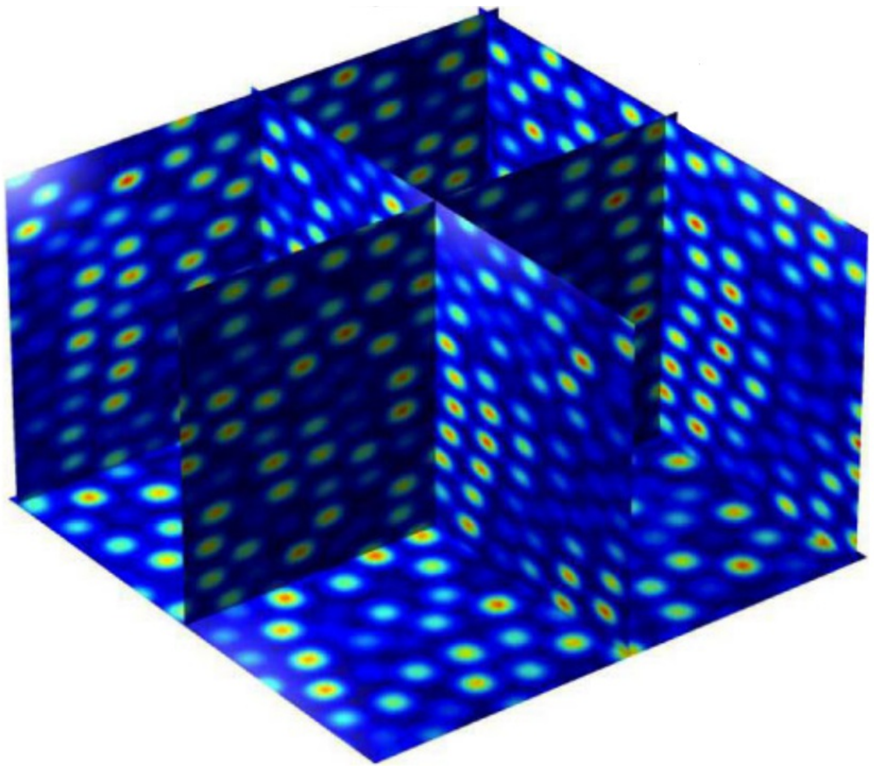
Dynamics in disorder - Many-body localization

Dynamics in long-range interacting systems - Rydbergs

Magnetic correlations and spin-charge separation in Hubbard chains

WHY LONG-RANGE INTERACTIONS?

Exotic matter

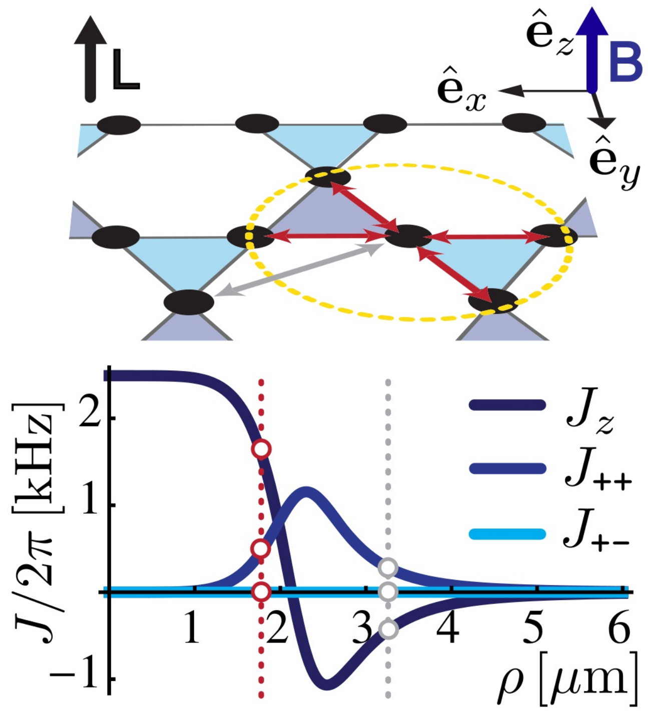


Supersolids *(Henkel, PRL 2010, Pupillo, PRL 2010, ...)*

Extended Hubbard model *(Dalla Torre, PRL 2006, ...)*

Dipolar fermions *(Li, Nat. Commun. 2015, ...)*

Quantum magnets



Switchable spin dependent interactions

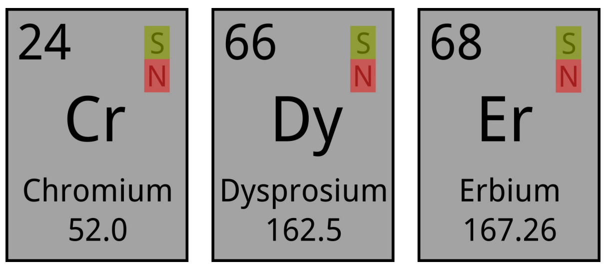
Topology *(van Bijnen, PRL 2015)*

Frustration *(Glaetzle, PRL 2015)*

Floquet phases *(Potirniche, arXiv:1610.0761, ...)*

Possible realizations

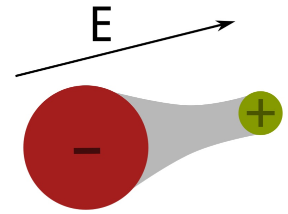
Magnetic atoms



$$V = \frac{\mu_0 \mu^2}{4\pi r^3}$$

1 Hz at 1 μm

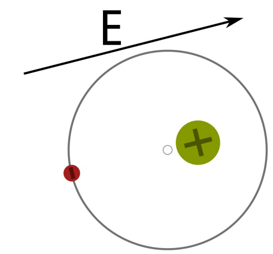
Groundstate molecules



$$V = \frac{d^2/\epsilon_0}{4\pi r^3}$$

1 kHz at 1 μm

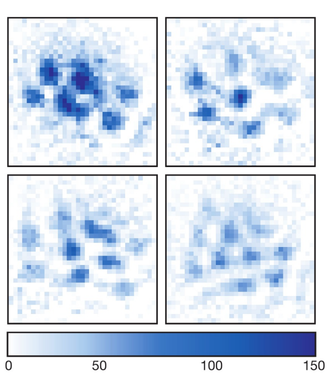
Rydberg atoms



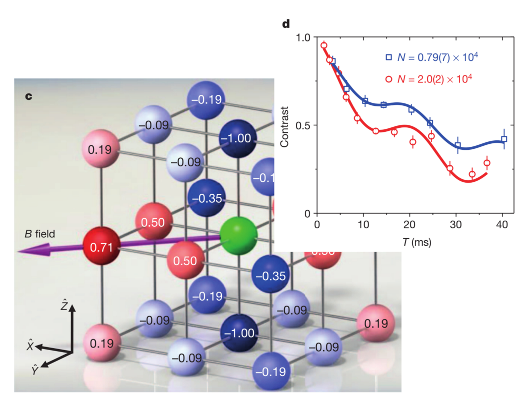
$$V = \frac{d^2/\epsilon_0}{4\pi r^3}$$

100 GHz at 1 μm

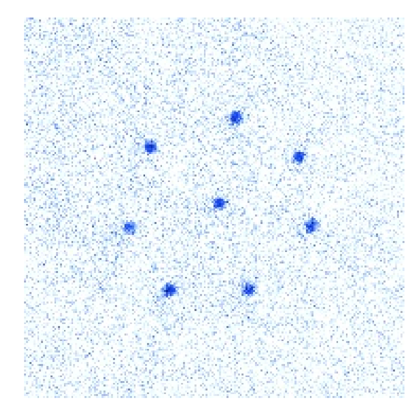
State-of-the art:



Stuttgart, Innsbruck, Paris, Stanford, ...



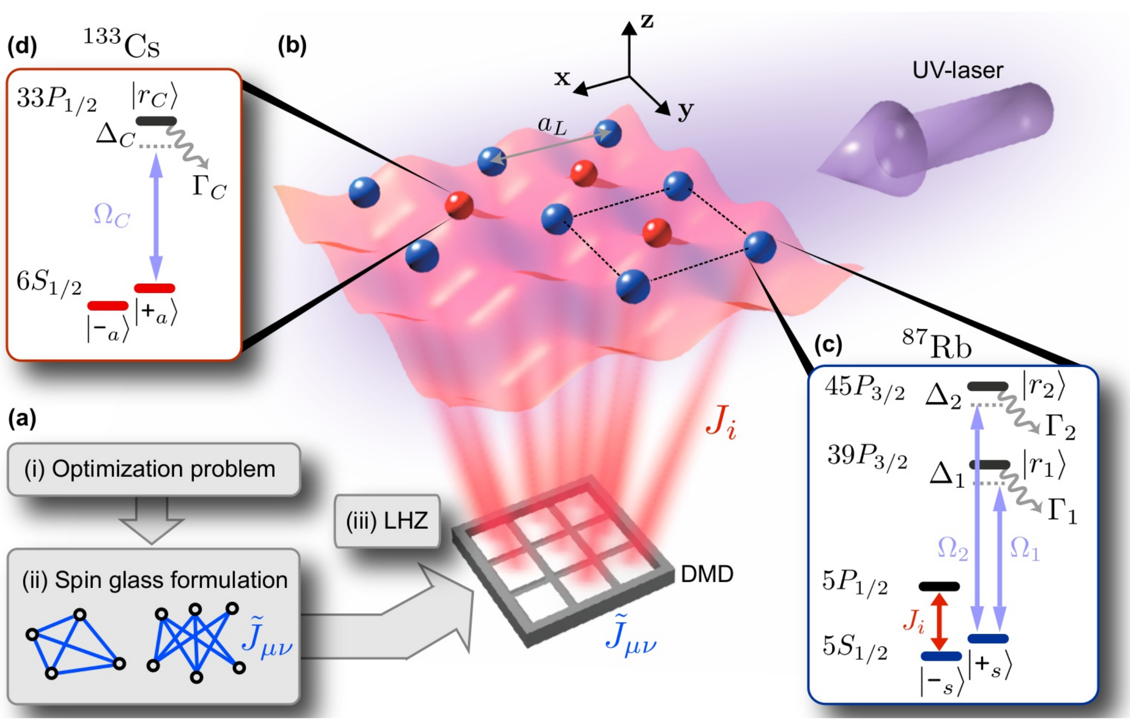
Boulder, MIT, Heidelberg, Hannover, Munich, Innsbruck, ...



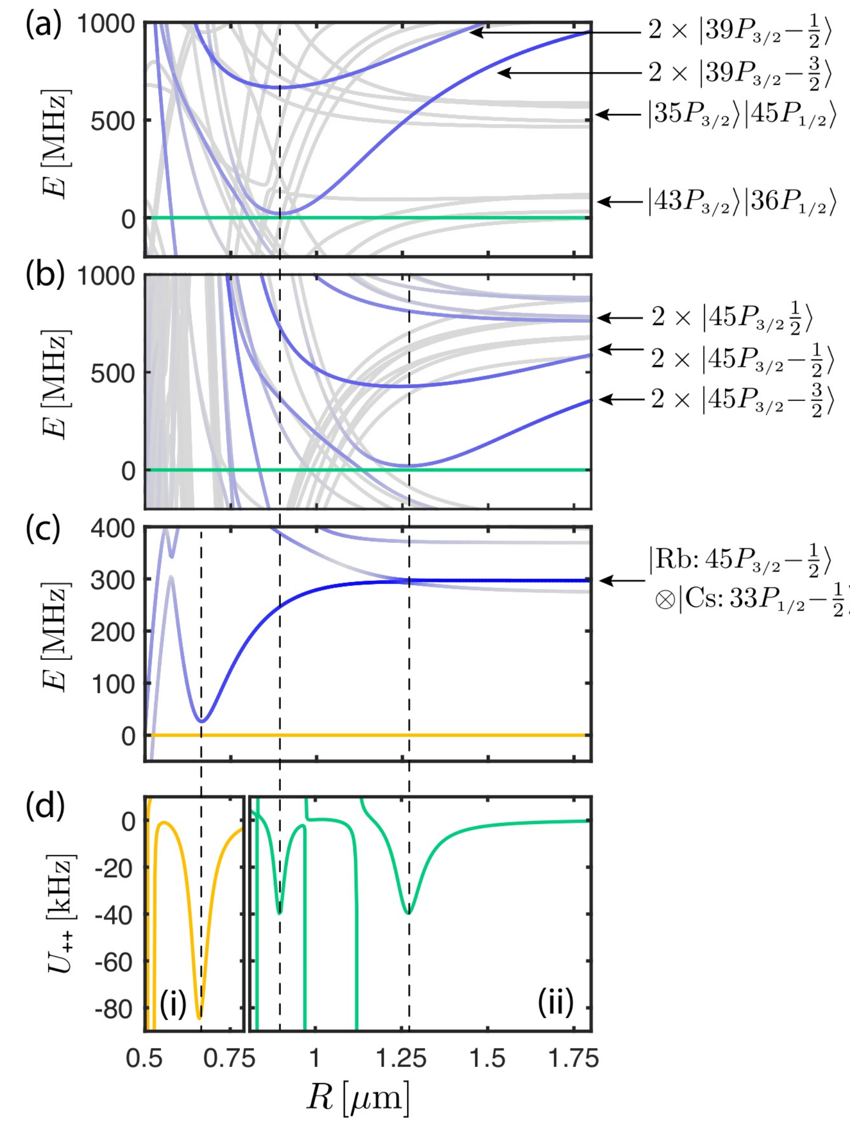
Munich, Paris, Pisa, Sandia, Heidelberg, Stuttgart, Rice, Maryland, Ann Arbor, Madison ...

Future quantum technology?

A Rydberg based quantum annealing architecture



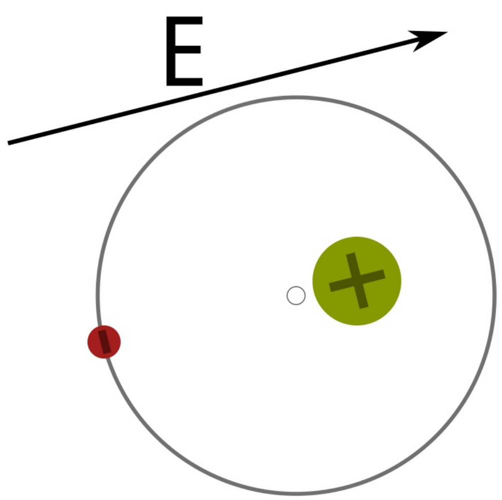
Glaetzle, et al. arXiv:1611.02594



Lechner, et al., Science Advances, **1**, e1500838 (2015)

INTERACTIONS BETWEEN RYDBERG ATOMS

Properties



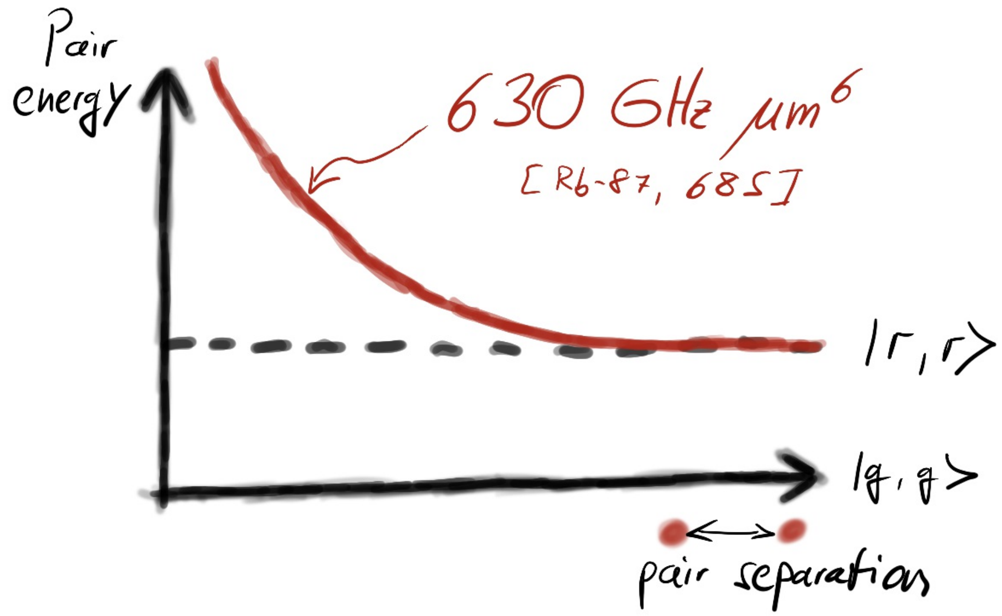
Atoms with large principal quantum number n

Long lifetime τ_r

Extreme polarizibility $p \propto n^7 \quad \longrightarrow$ strong interactions

Gallagher: Rydberg Atoms, 1994 | Saffman, RMP 2010

Extreme interactions



Extreme van der Waals interactions $V = -\frac{C_6}{r^6}$

$$C_6 \propto n^{11} \quad \rightarrow_{n=60} \quad C_6 \approx 600\,\mathrm{GHz}\,\mu\mathrm{m}^6$$

$$\tau_r \propto n^2 \quad \rightarrow_{n=60} \quad \tau_r \approx 100\,\mu\mathrm{s}$$

Saffman, RMP 2010

Strongly state dependent interactions

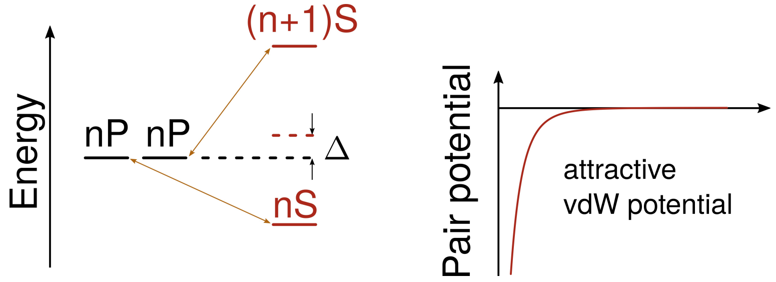
Van-der-Waals interactions = second order dipole interactions

dipole-dipole: $V_{d_1,d_2} = \frac{\mathbf{d_1}\cdot\mathbf{d_2} - 3(\mathbf{d_1}\cdot\mathbf{n})(\mathbf{d_2}\cdot\mathbf{n})}{r^3}$

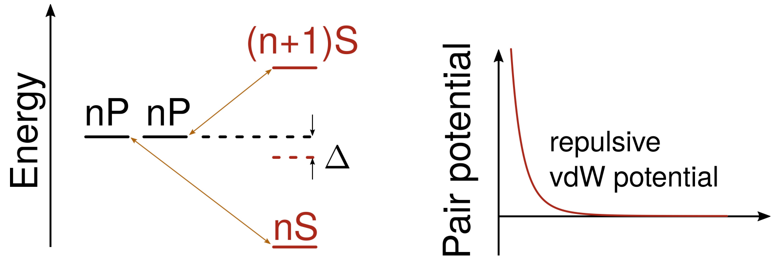
(vanishes for two atoms in the same state)

van-der-Waals: $V^{(2)}_{d_1,d_2} = -\sum_i \frac{V_{d_1,d_2}|i\rangle\langle i|V_{d_1,d_2}}{\Delta_i}$

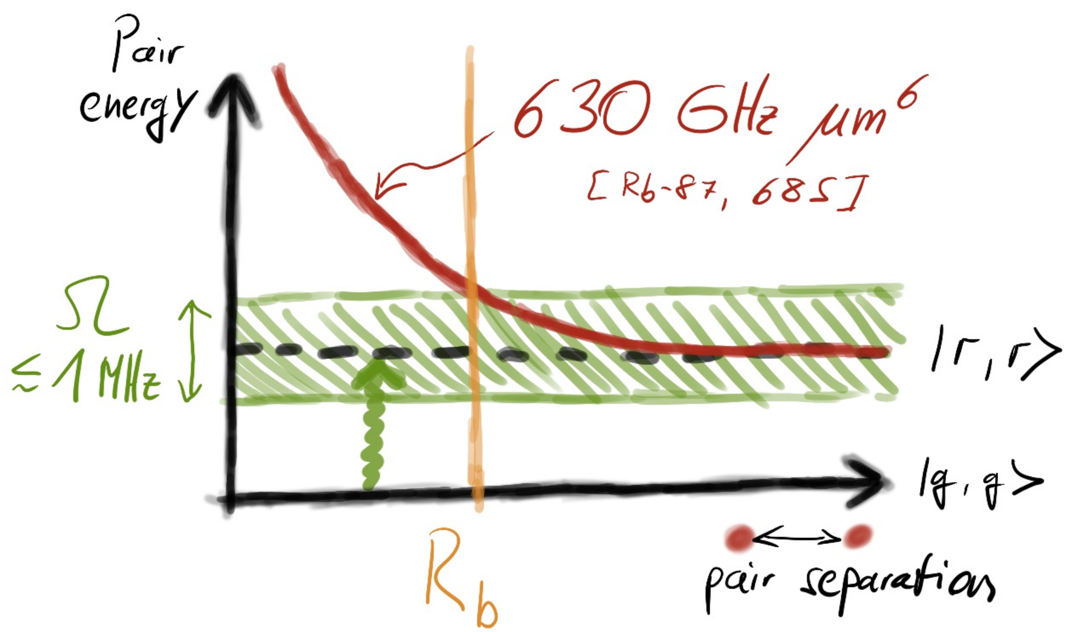
Attractive ($\Delta > 0$)



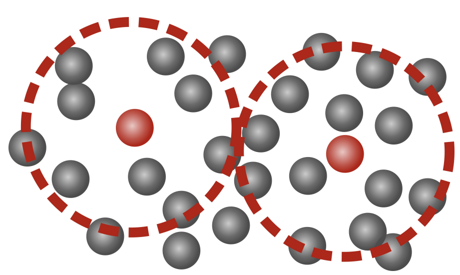
Repulsive ($\Delta < 0$)



Dipole blockade



Two-body interactions exceed all energy scales on μm scales!



$\rightarrow$ *Excitation blockade* $R_b = \sqrt[6]{C_6/\hbar\Omega} \approx 5\,\mu\text{m}$

Jaksch, PRL 2000 | Lukin, PRL 2001

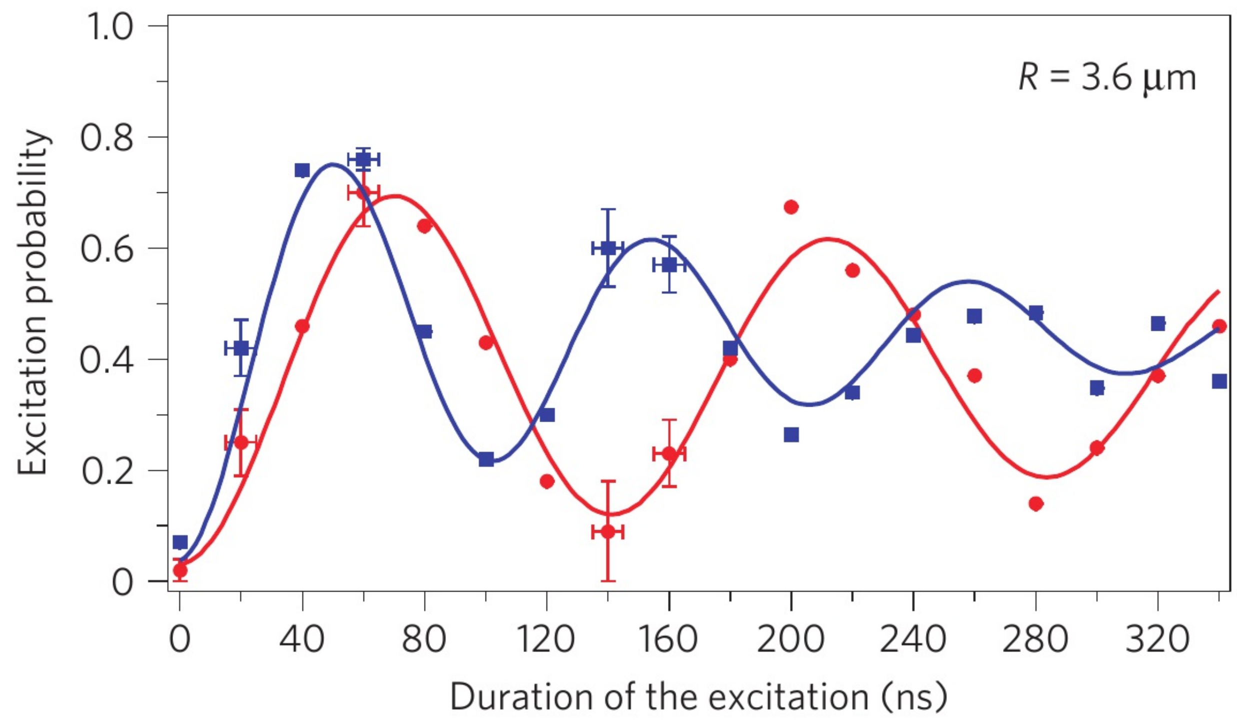
To keep in mind

Atomic motion is negligible (μs timescales)

Interaction is state selective, we start always in a non-interacting state

Naturally leads to spin-$\frac{1}{2}$ Hamiltonians

Driving two blockaded atoms



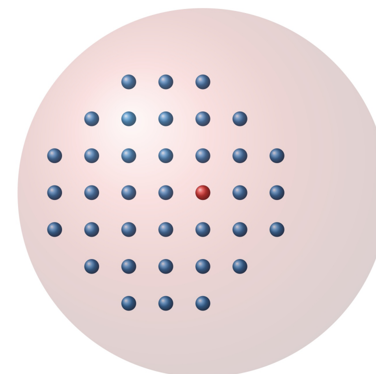
from Gaetan, Nat. Phys. 2009

Symmetrically shared excitation: $|gg\rangle \leftrightarrow (|rg\rangle + |gr\rangle)/2$

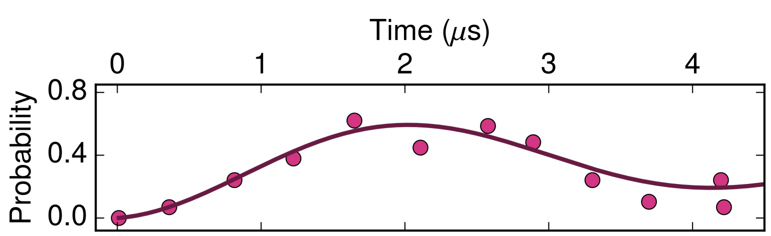
Rabi frequency: $\Omega_{\text{eff}} = \sqrt{2}\Omega$

Gaetan, Nat. Phys. 2009 | Urban, Nat. Phys. 2009 | gate: Isenhower, PRL 2010

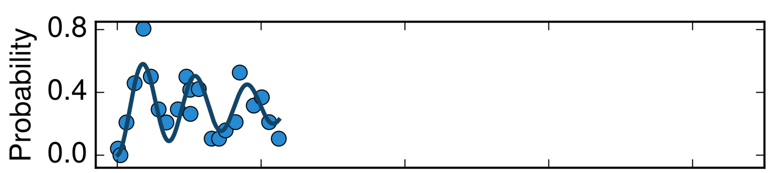
Driving many blockaded atoms



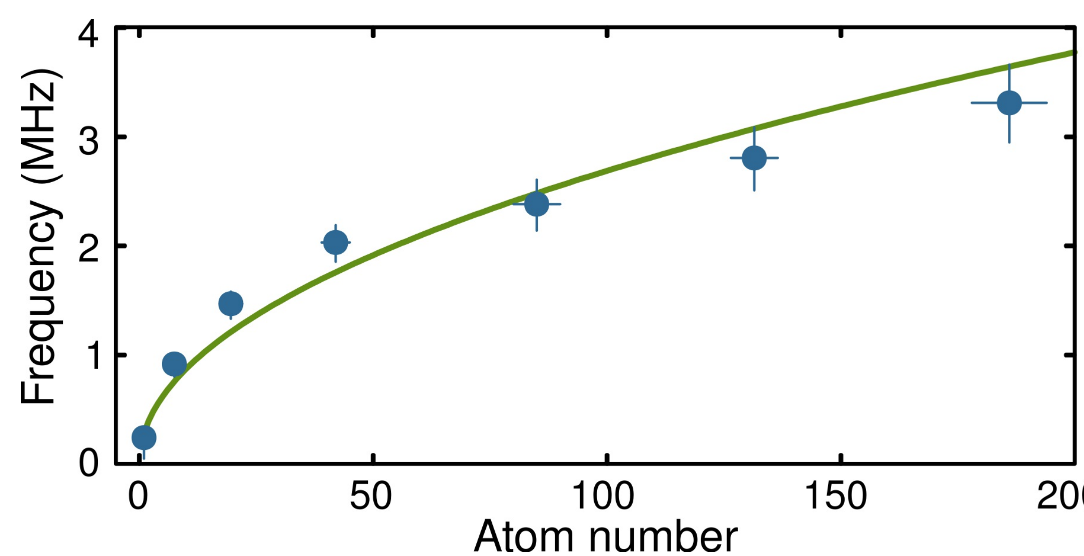
Coupling to W-state: $\Omega_{\text{eff}} = \sqrt{N}\Omega$



1 atom



140 atoms

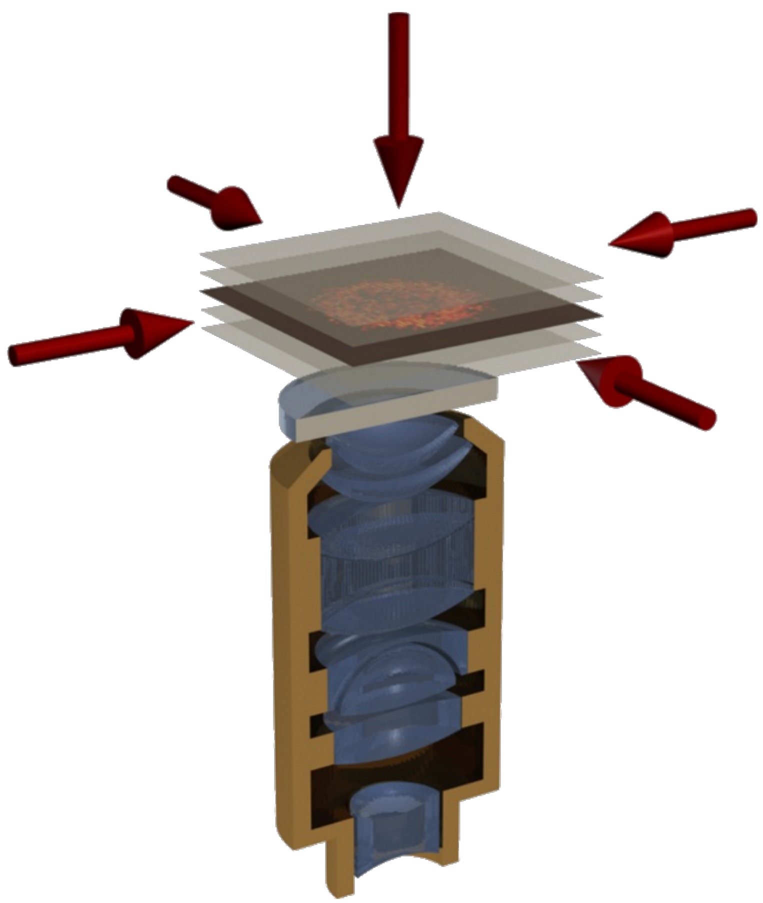


Zeiher, PRX 2015 | also: Dudin, Nat. Phys. 2012 | Ebert, PRL 2014 | Labuhn, Nature 2016

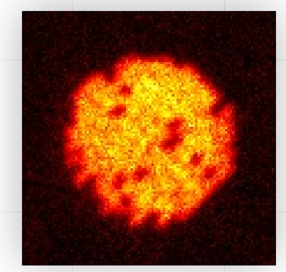
RYDBERG MANY-BODY EXPERIMENTS

Detecting single Rydberg atoms with high spatial resolution

Large working distance microscope,
no nearby surfaces!



Microscope works only for
ground state atoms!



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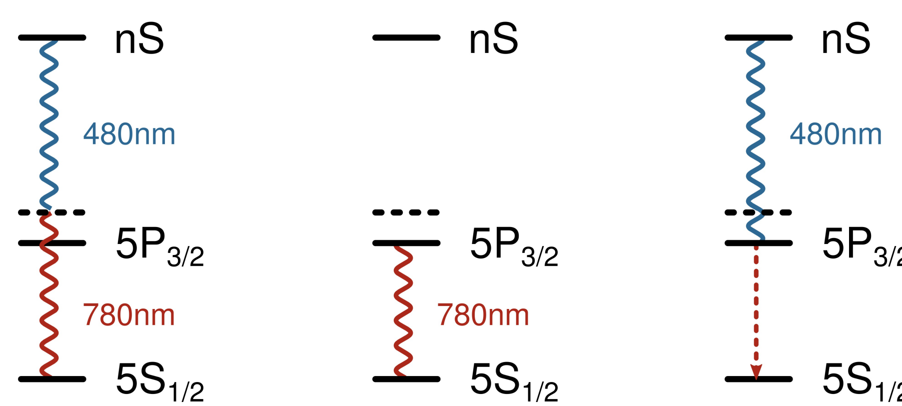
Excitation and "Blow out"



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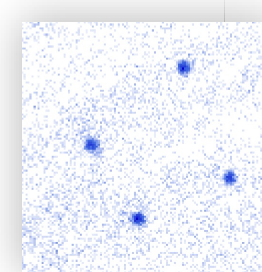
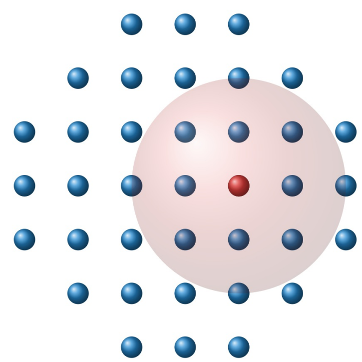
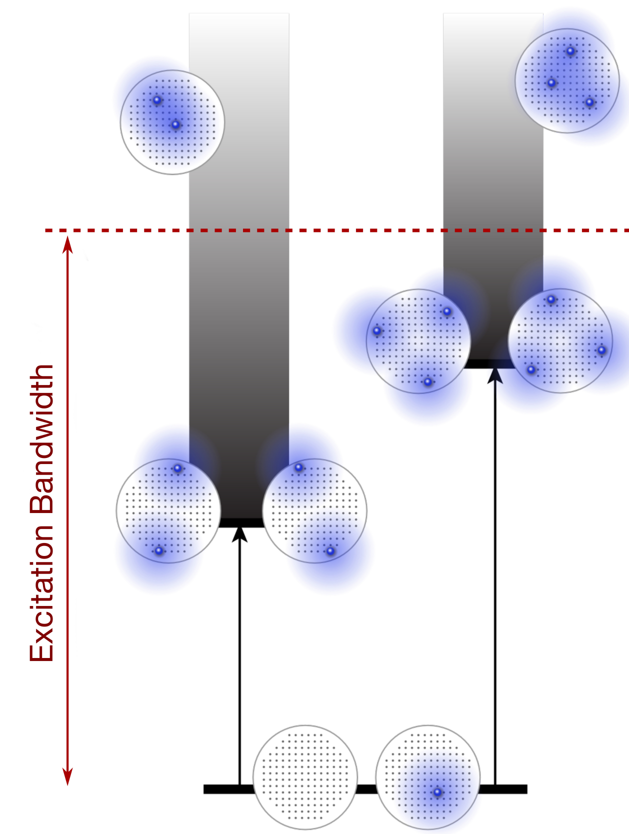


Breaking the blockade



Partial blockade

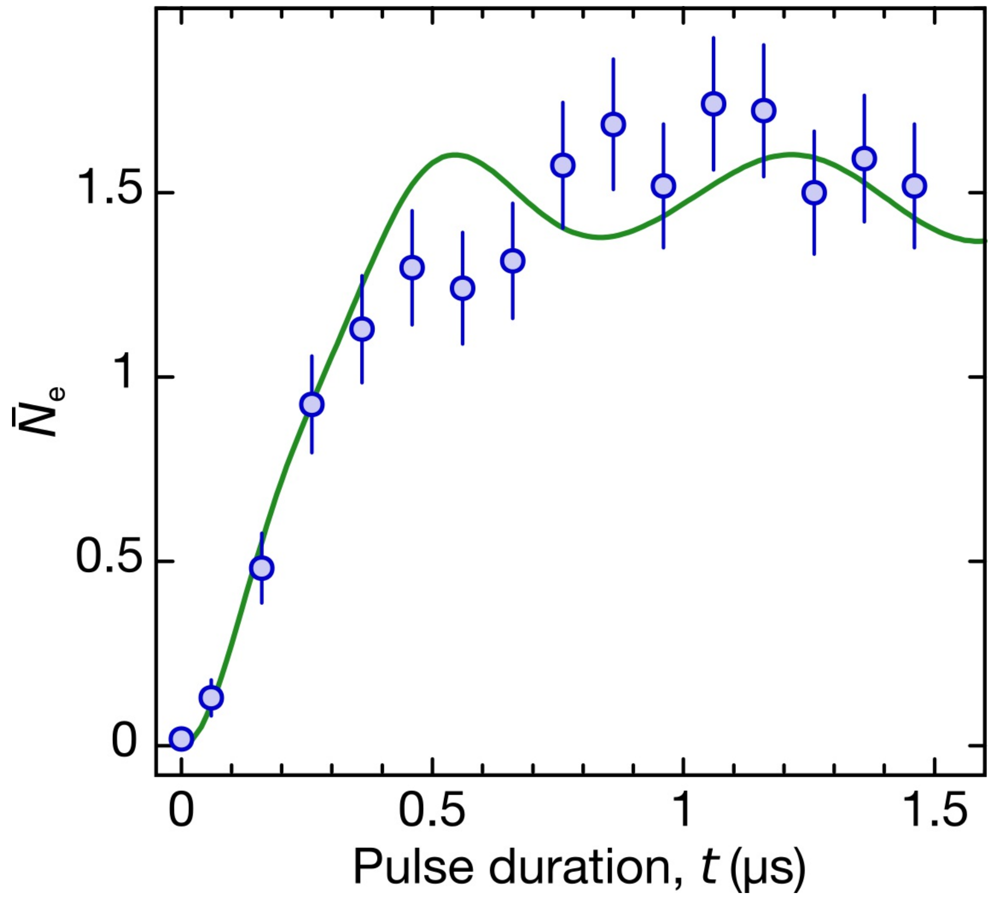


Energetics

Start in ground state, then pulse on Rydberg laser for variable time

Only certain spatial configurations accessible

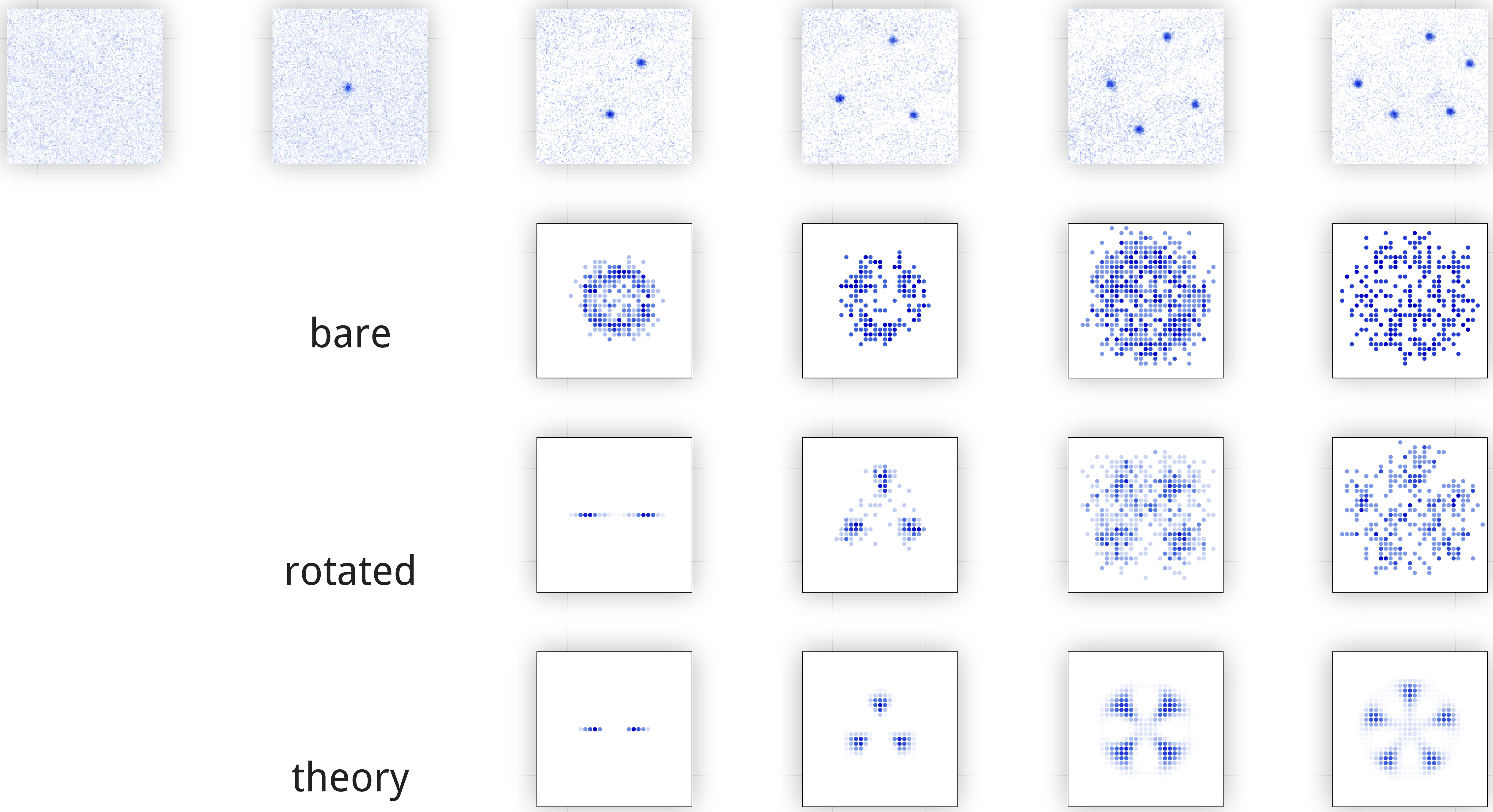
Excitation dynamics



Excitation "appears" incoherent

Schauß, Nature 2012 | also : Labuhn, Nature 2016

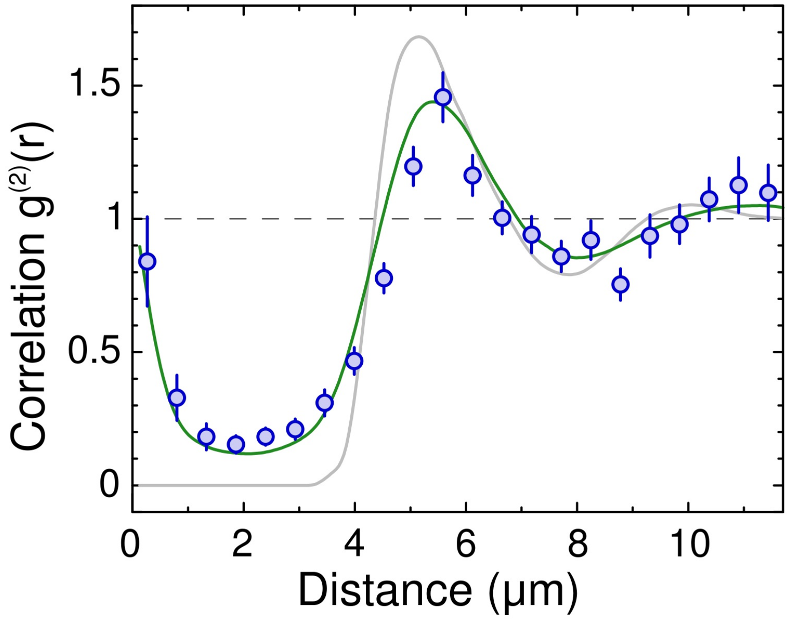
A local look



Schauß, Nature 2012

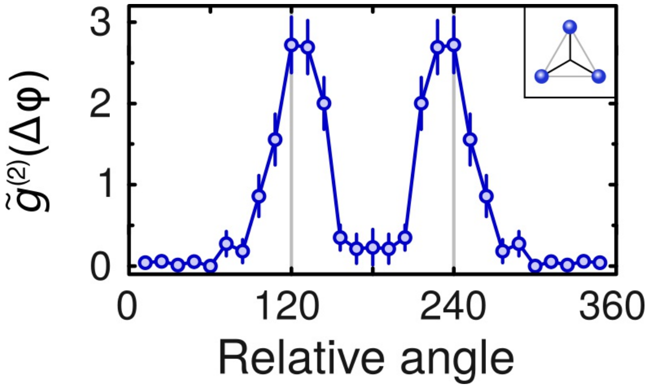
Correlations

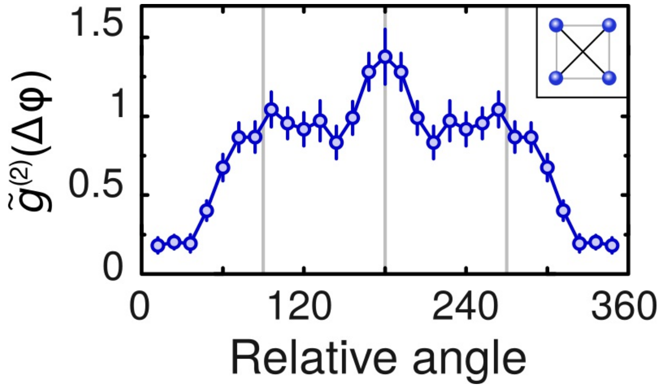
Distance correlations (radial $g^{(2)}$)

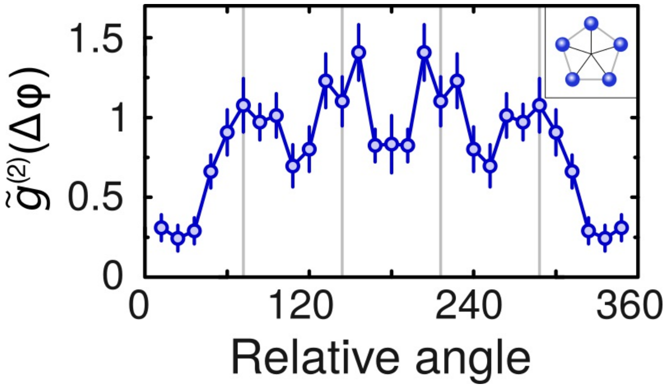


Blockade radius ≈ 10 sites

Azimuthal correlations

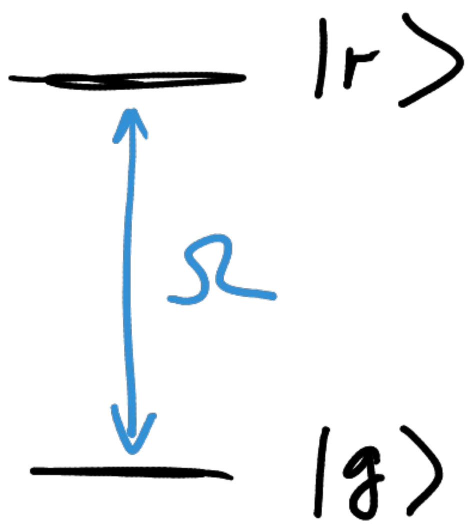


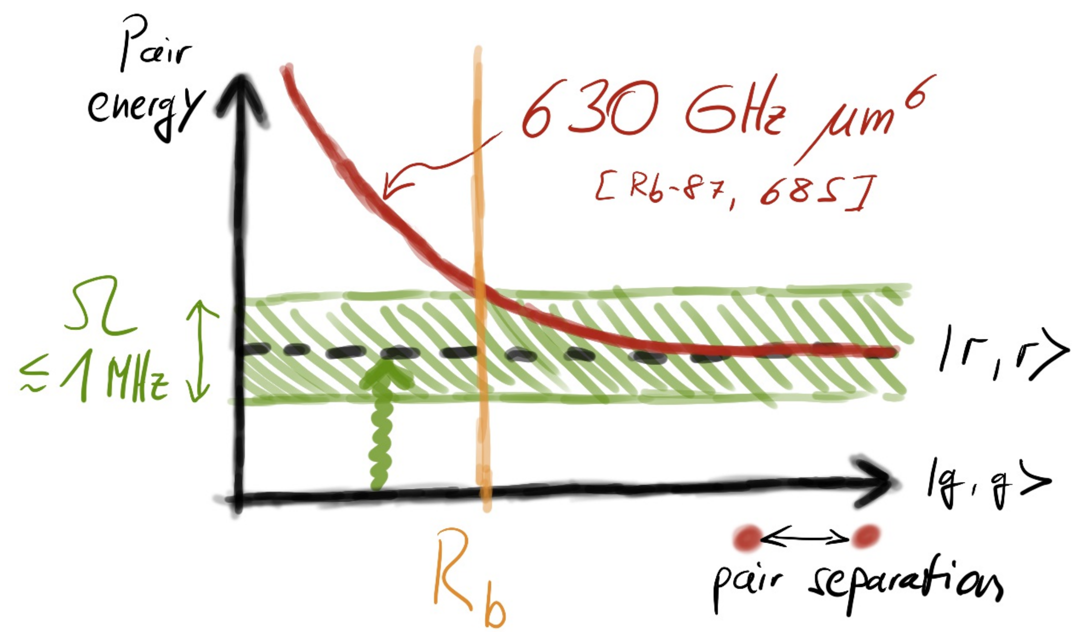




RYDBERG DRESSING

Limitations of resonant excitation in dense systems



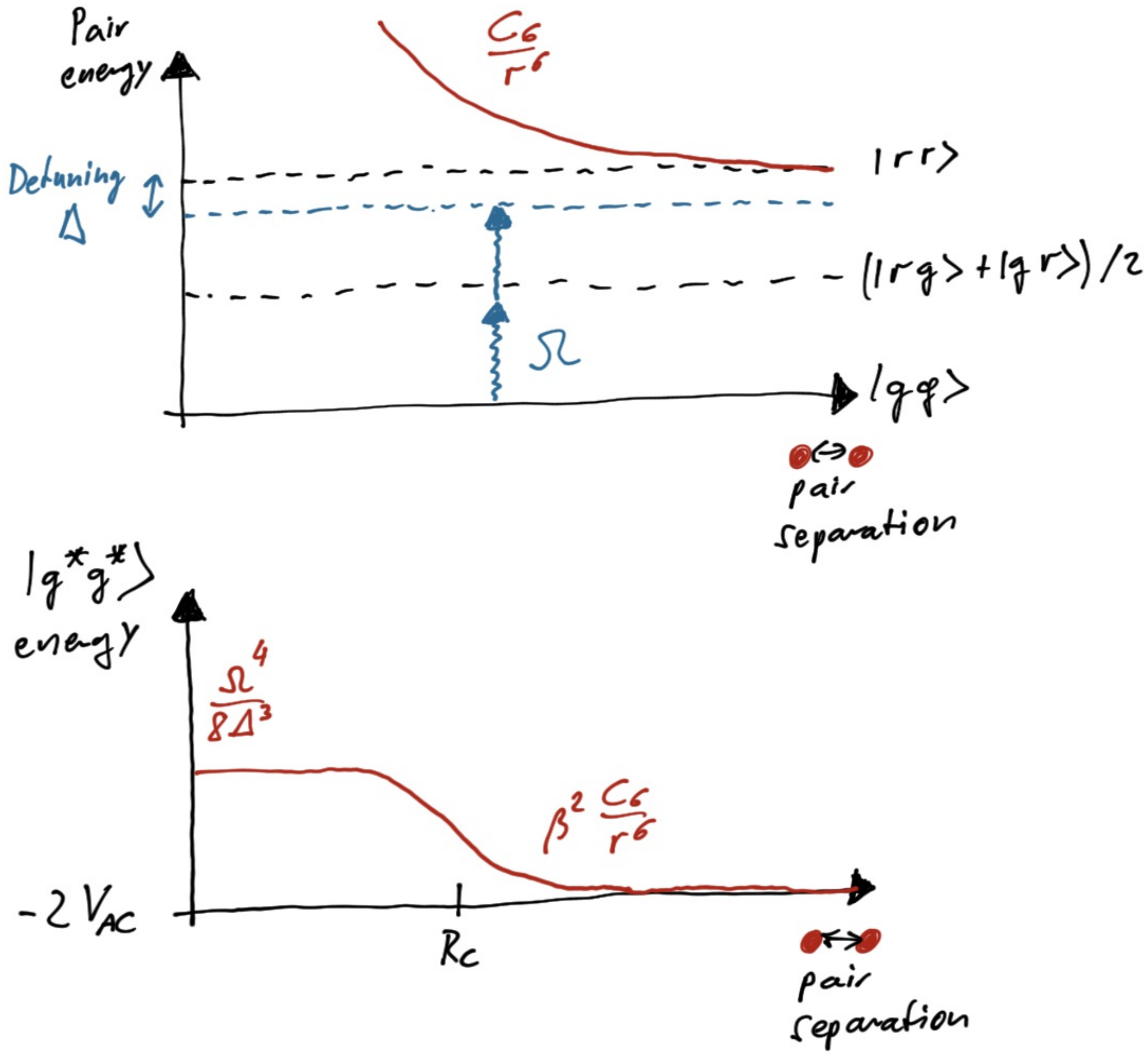


$$\hat{H} = \sum_{i<j} V_{i,j} \hat{S}_i^z \hat{S}_j^z + \hbar\Omega \sum_i \hat{S}_i^x - \hbar\Delta \sum_i \hat{S}_i^z$$

Interaction always dominant, no independent control

Relevant interaction strength linked to the laser parameters

Taming the interactions via detuning



Far detuned regime

$$|g\rangle \;\rightarrow\; |g\rangle + \frac{\Omega}{2\Delta}|r\rangle$$

Effective parameters

$$V_{i,j} = (\tfrac{\Omega}{2\Delta})^4 C_6/(R_C^6 + r_{i,j}^6)$$

$$V_0 = \frac{\Omega^4}{8\Delta^3}$$

$$R_C = \sqrt[6]{C_6/2\hbar\Omega}$$

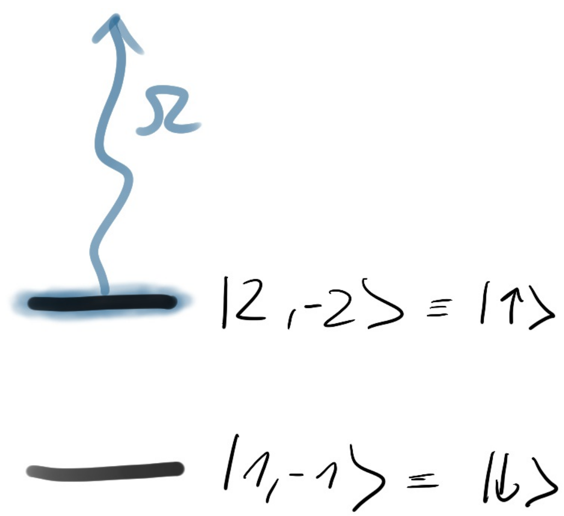
$$\tau = (2\Delta/\Omega)^2 \tau_r$$

Requires very strong coupling Ω

Santos, PRL 2000 | Bouchoule, PRA 2002 | Honer, PRL 2010 | Johnson, PRA 2010

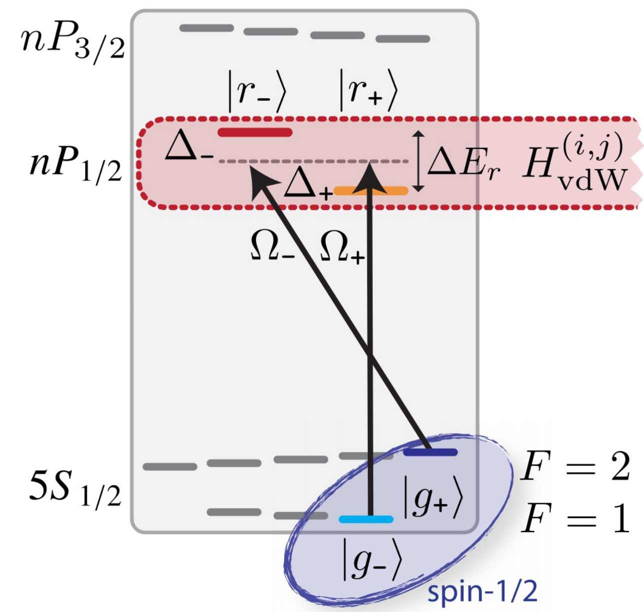
Tailored quantum magnets

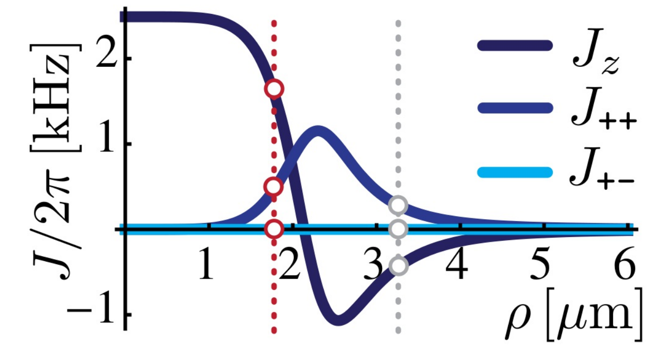
Ising interactions



$$\hat{H} = \sum_{i<j} V_{i,j}\hat{S}_i^z \hat{S}_j^z$$

Complex interactions





$$\hat{H} = \sum_{i<j}[J^z_{i,j}\hat{S}_i^z\hat{S}_j^z + (J^{+-}_{i,j}\hat{S}_i^+\hat{S}_j^- + J^{++}_{i,j}\hat{S}_i^+\hat{S}_j^+ + \mathrm{h.c.})/2]$$

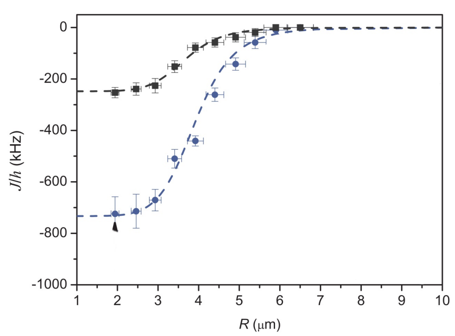
Single atom parameters ($\hat{S}_i^x$, $\hat{S}_i^z$) controllable

Interaction and single atoms terms switchable!

Glaetzle, PRL 2015 | van Bijnen, PRL 2015

State of the art in 2015

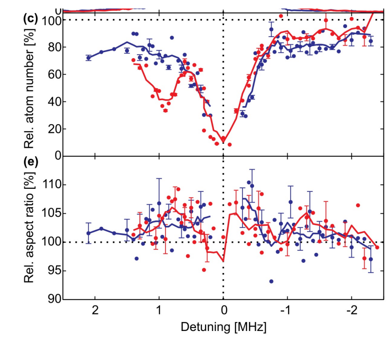
Two atoms, high Rabi



Jau, Nat. Phys. 2016

works!

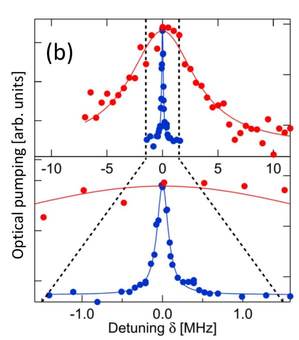
3d BEC, low Rabi



Balewski, NJP 2014

No signal!

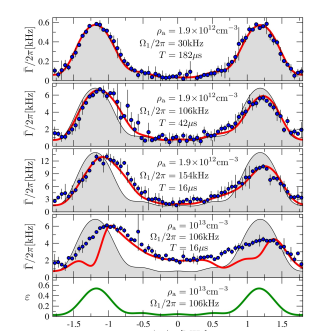
3d lattice, low Rabi



Goldschmidt, PRL 2016

Strong line broadening

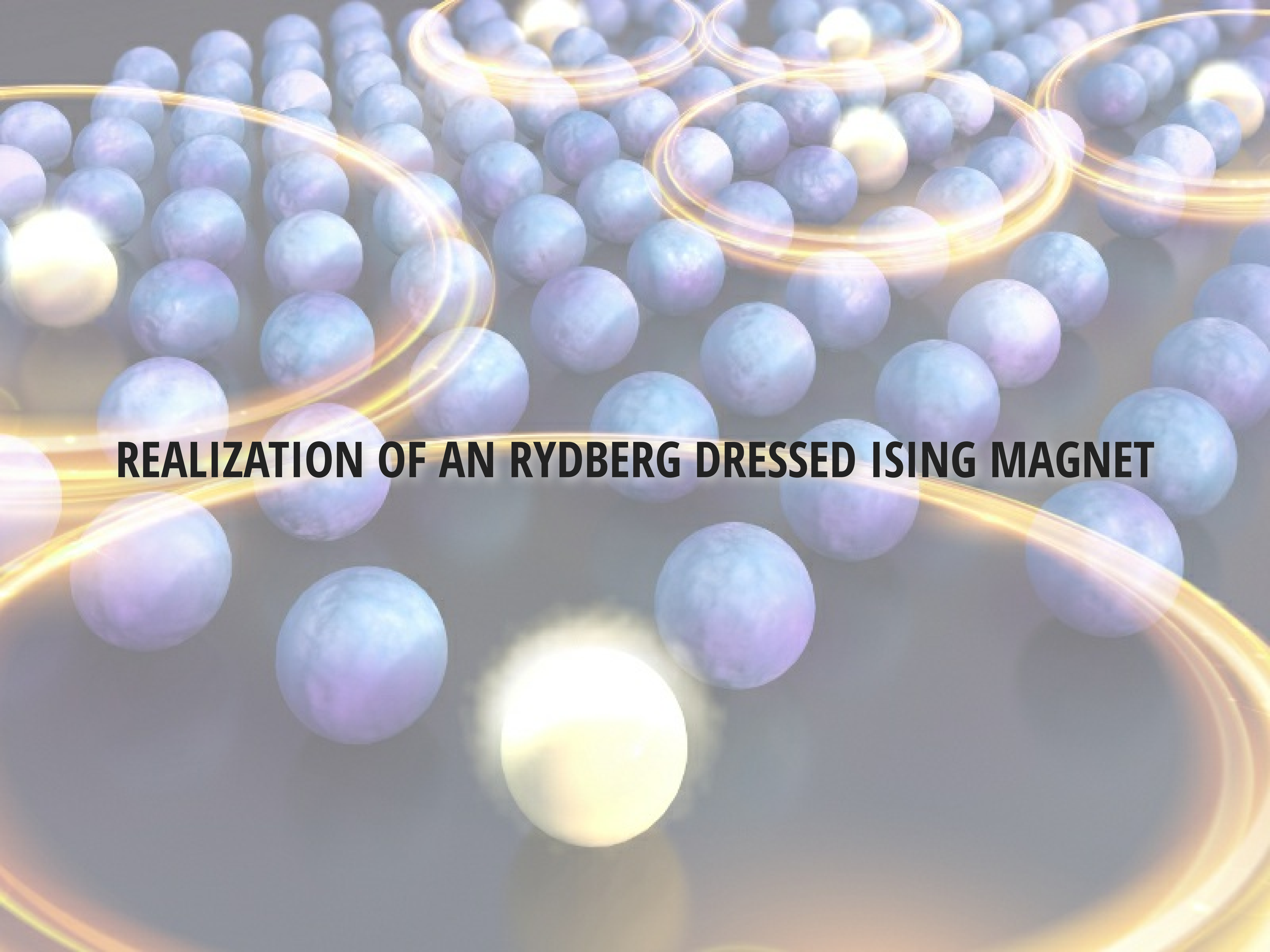
Cold Sr gas, low Rabi



Gaul, PRL 2016

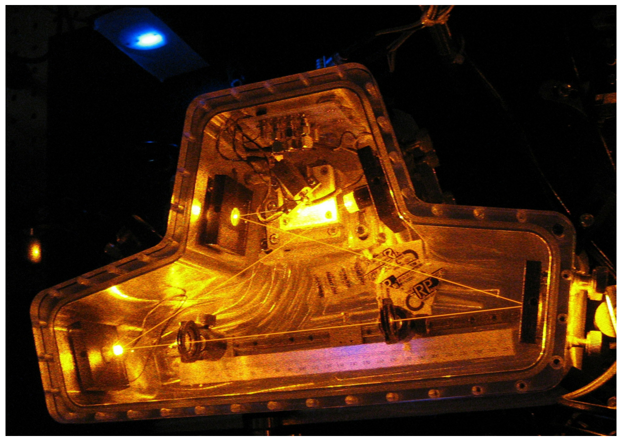
Broadening

Very recent: Jia, arXiv:1705.07475



REALIZATION OF AN RYDBERG DRESSED ISING MAGNET

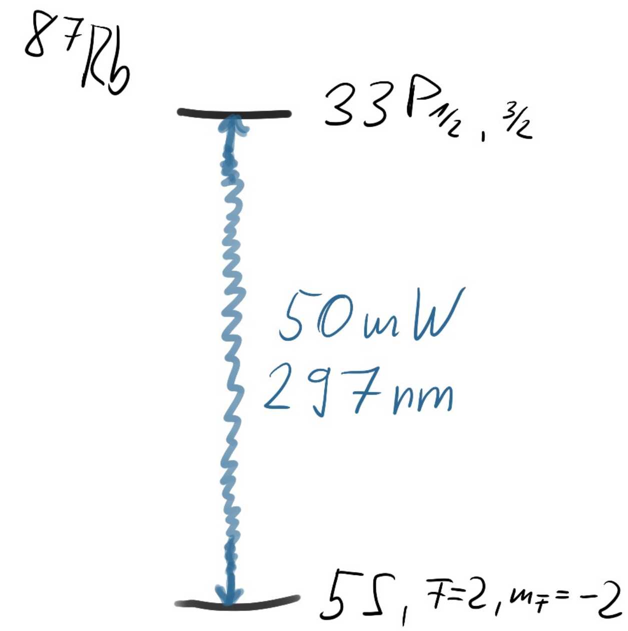
A new laser system



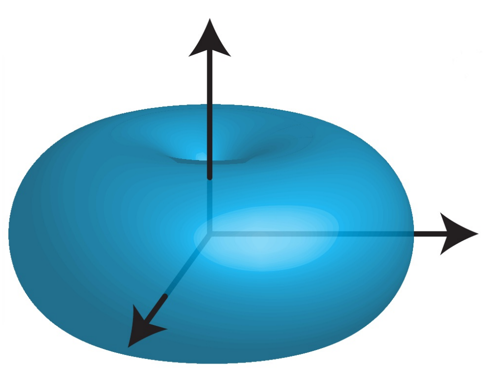
UV-coupling to *P-states*

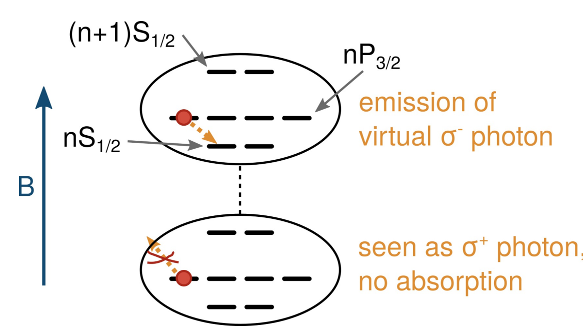
High Rabi frequencies

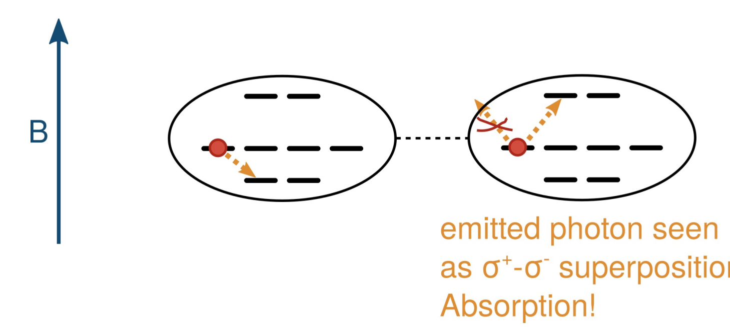
$\Omega \approx 2\pi \cdot 8\,\text{MHz}$



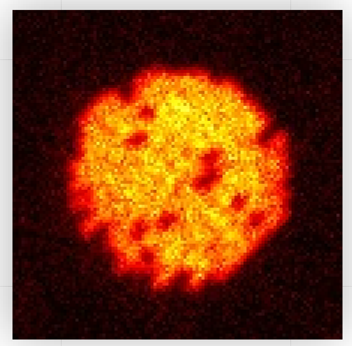
p-states: spatial interaction anisotropy controllable

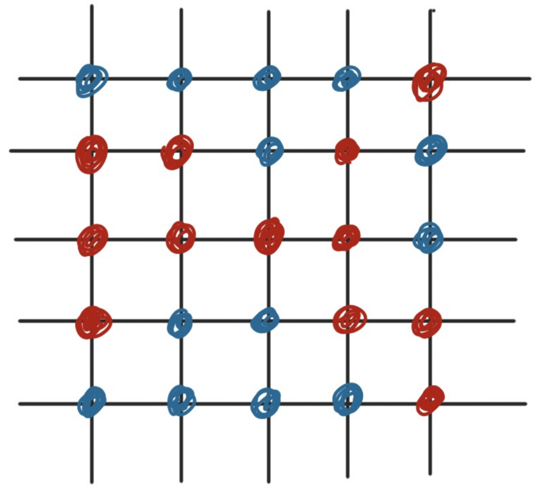


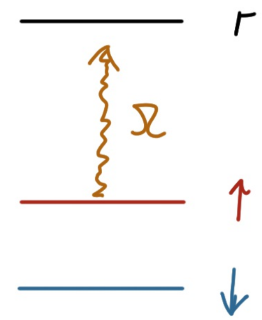


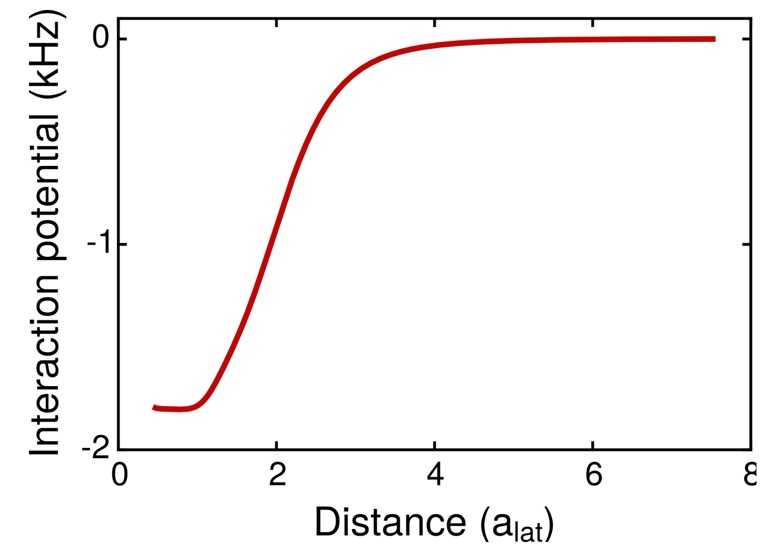


The system









Small (200 atoms) 2d lattice system

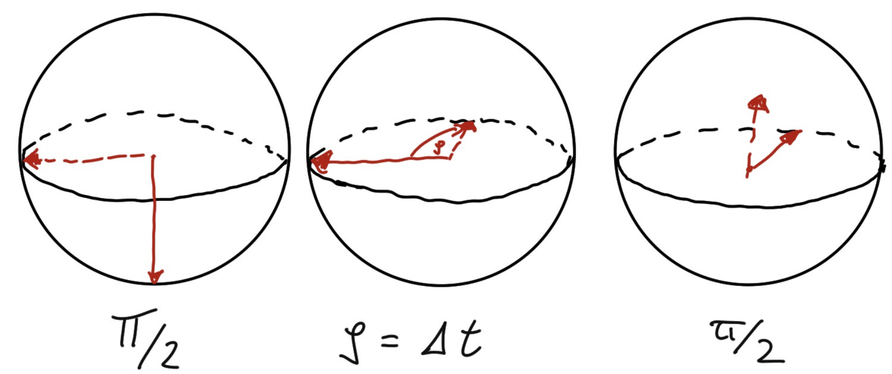
Long-range Ising interactions with soft-core potential

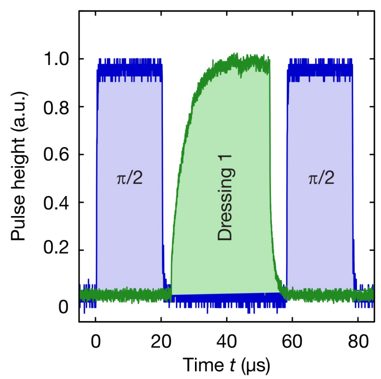
$$\hat{H} = \sum_{i<j} V_{i,j} \hat{S}_i^z \hat{S}_j^z + \sum_i (\delta + \delta_{C,i}) \hat{S}_i^z$$

Strongest terms are single particle effects:

- Light shift $\delta \propto \frac{\Omega^2}{\Delta}$
- "mean field" $\delta_{C,i} = \frac{N_{\text{eff}}}{2} \frac{\Omega^4}{8\Delta^3}$

Many-body Ramsey interferometry



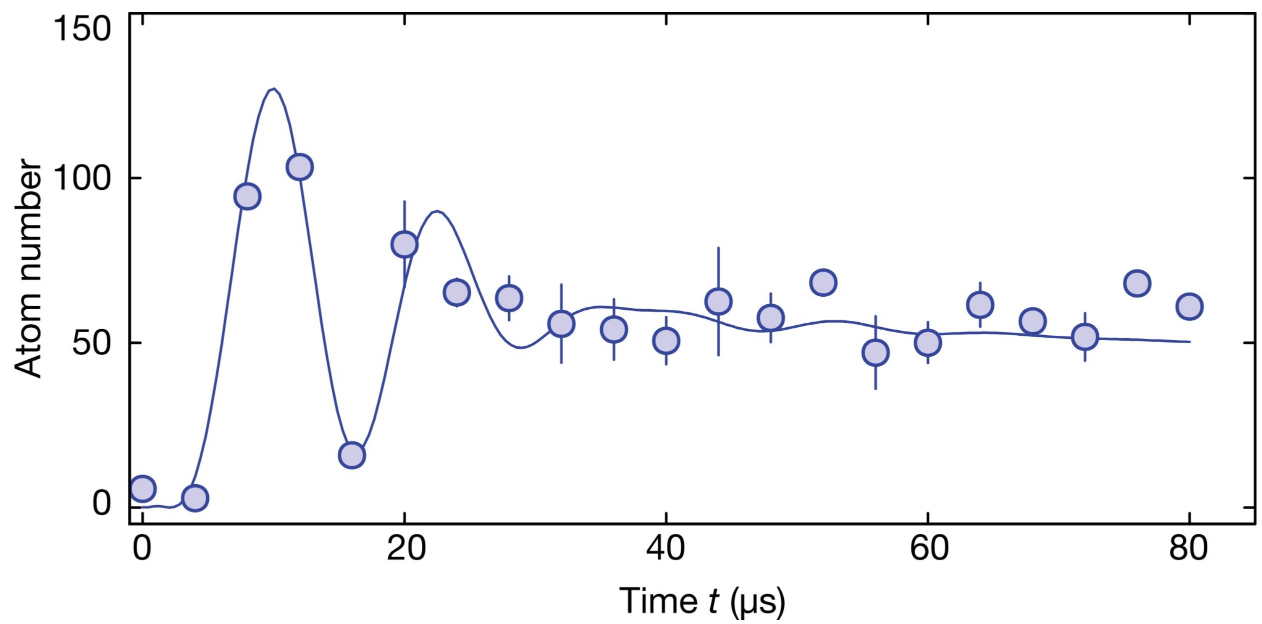


Precise spin rotation by microwaves

Evolution with $e^{-i\hat{H}t/\hbar}$

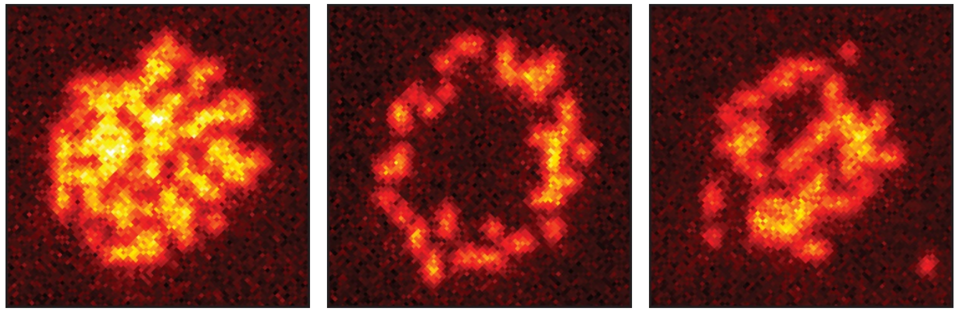
Measures mostly the accumulated single particle phase

Interaction induced dephasing



Oscillation: Light shift

Fast dephasing: mean field



$\longrightarrow$ time $\longrightarrow$

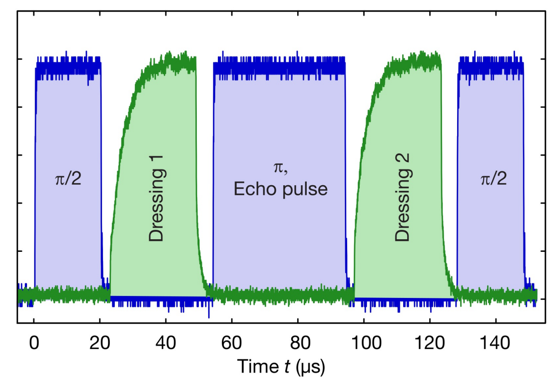
$\delta_{C,i} = \sum_j \frac{\Omega^4}{16\Delta^3} \frac{1}{1+(r_{i,j}/R_c)^6}$ depends on the number of neighbors!

IMAGING THE INTERACTION POTENTIAL

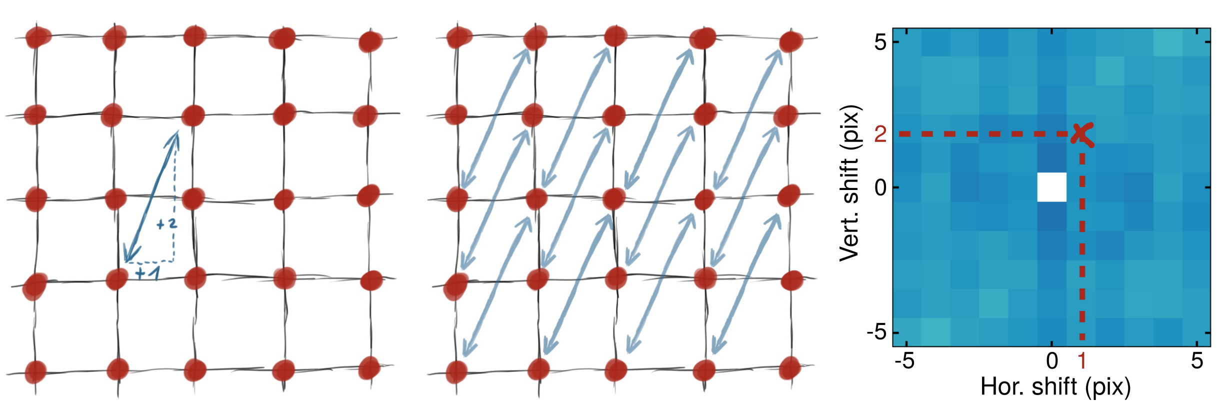
Focussing on correlations

$$\hat{H} = \sum_{i<j} V_{i,j} \hat{S}_i^z \hat{S}_j^z + \sum_i (\delta + \delta_{C,i}) \hat{S}_i^z$$

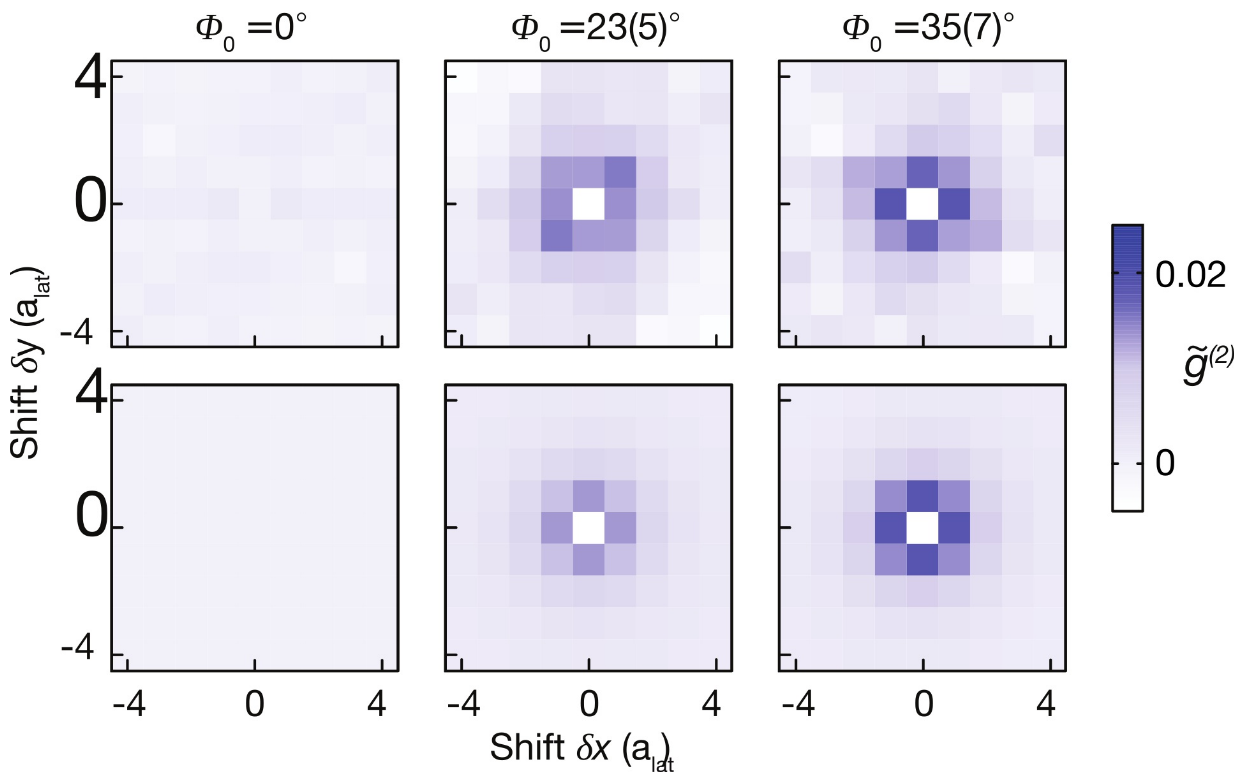
Spin echo to cancel single spin effects



Measure $g_{i,j}^{(2)} = \langle \hat{S}_i^z \hat{S}_j^z \rangle - \langle \hat{S}_i^z \rangle \langle \hat{S}_j^z \rangle$



Emergence of correlations



⟶ time ⟶

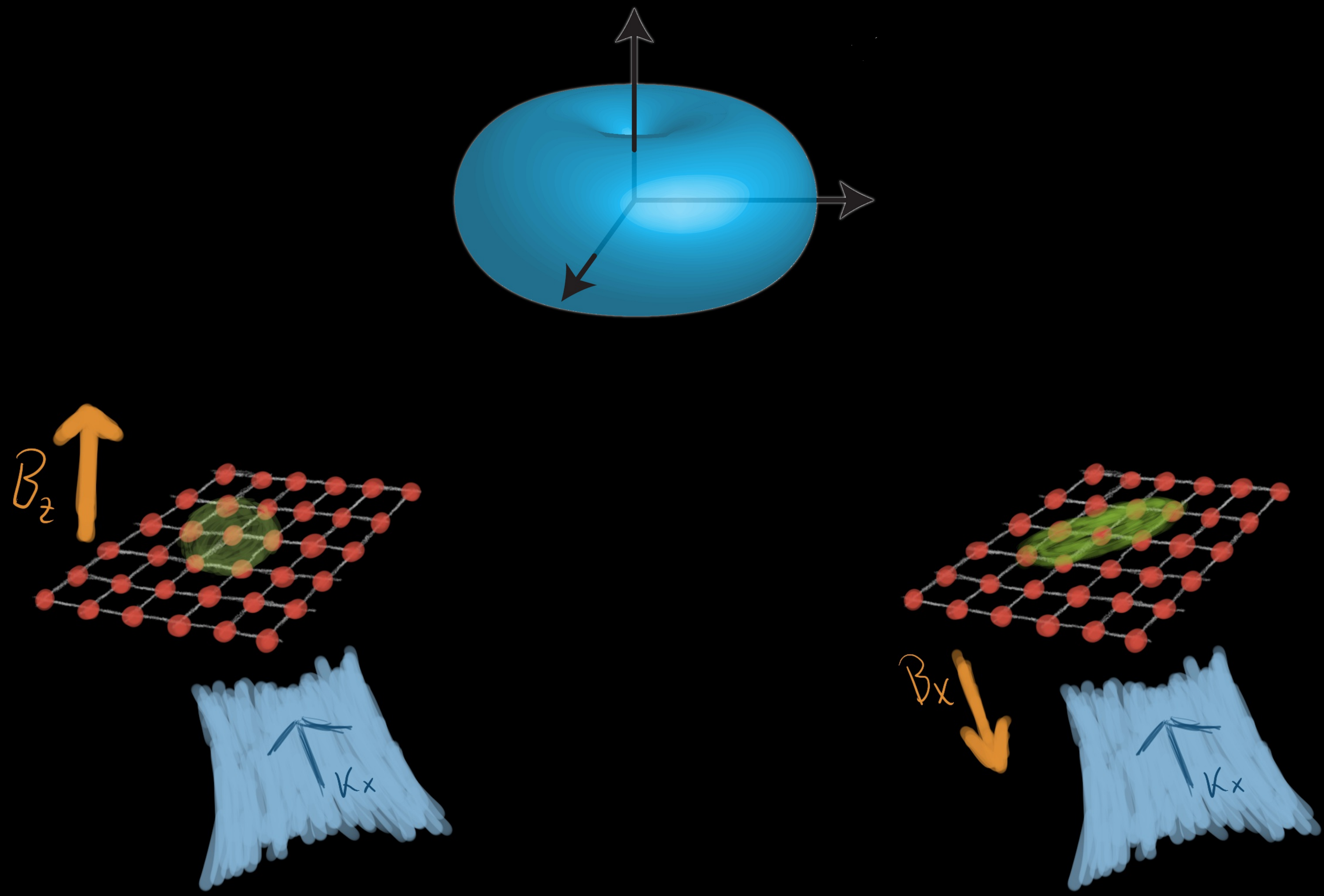
$$|\Psi(t)\rangle = e^{-it/\hbar \sum_{i<j} V_{i,j} \hat{S}_i^z \hat{S}_j^z} |\Psi(0)\rangle$$

@ Very short time $t \ll 1/V_0$:

$$g_{ij}^{(2)} \propto \varphi_{ij}(t)^2 = (V_{ij}t)^2$$

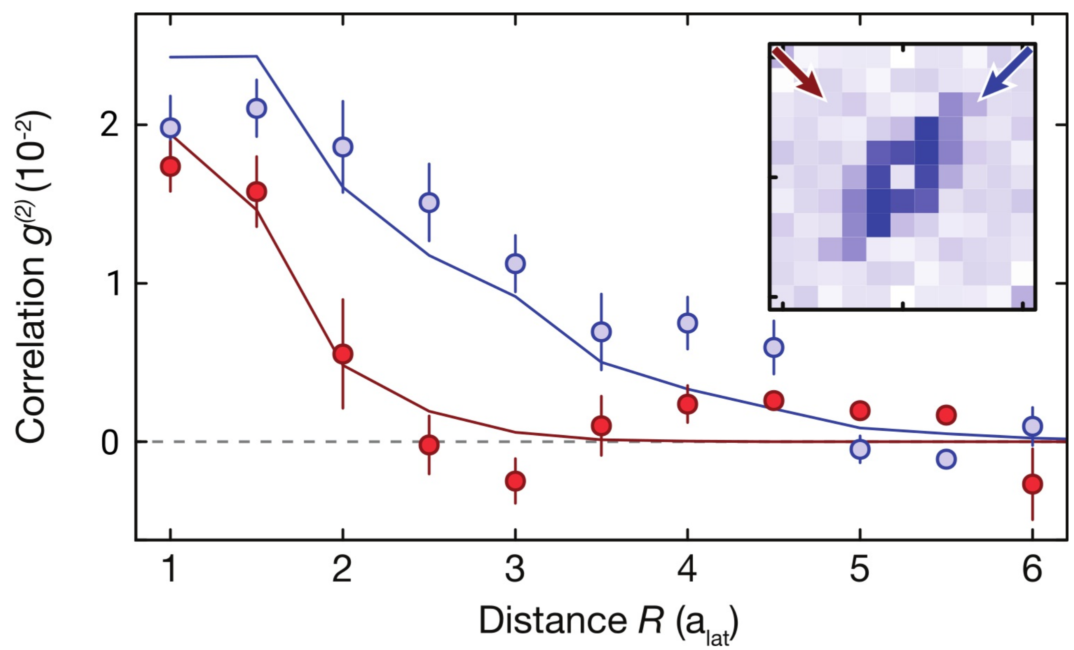
Direct "imaging" of the interaction potential $V_{i,j} = V_0/(1 + (r_{i,j}/R_C)^6)$

Isotropy control



Anisotropic correlations

Just switching the magnetic field direction ...



Clearly **anisotropic correlations** ($P_{3/2}$ state)!

Summary and prospects

Correlated excitation of Rydberg many-body systems

Rydberg dressing in 1D and 2D

Very good lifetime in 1D: $V_0 \cdot \tau = 90$!

Long time revivals demonstrate coherence

Prospects:

MBL, Floquet and long-range interactions:
time crystals and spt phases.

Motion and long-range interactions:
Extended Hubbard model

Towards a Rydberg Quantum Annealer?

time crystals with NV-centers and ions: Choi, arXiv:1610.08057 | Zhang, arXiv:1609.08684