Accurate Rydberg quantum simulations of spin-1/2 models

ICQSIM — Paris — November 16, 2017

Theory

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Experiment

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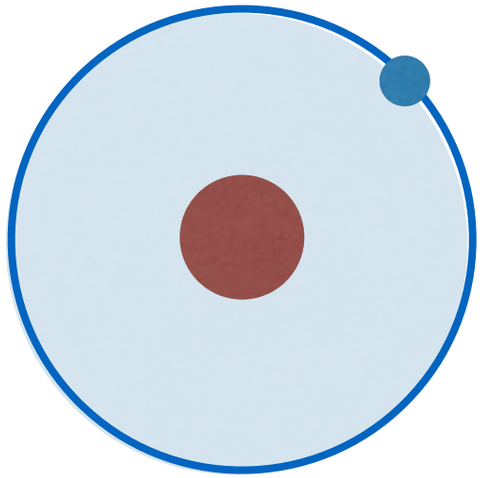
Rydberg quantum simulations of spin Hamiltonians

- **Strong interactions**

  I) dipole-dipole ~ n^4/R^3

  II) van der Waals ~ n^{11}/R^6, anisotropy possible

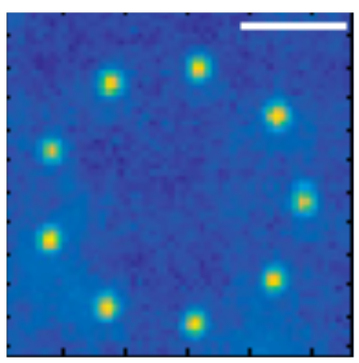
  III) cutoff potentials via Rydberg dressing



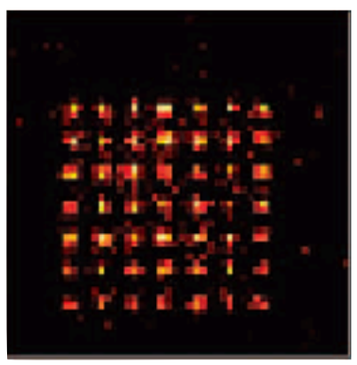
$n \gg 1$

- **Long radiative lifetime ~ n^3**

- **Defect-free arbitrary atom arrays experimentally realized**



H. Kim et al., Nat. Commun. **7**, 13317 (2016)



D. Barredo et al., Science **354**, 6315 (2016)

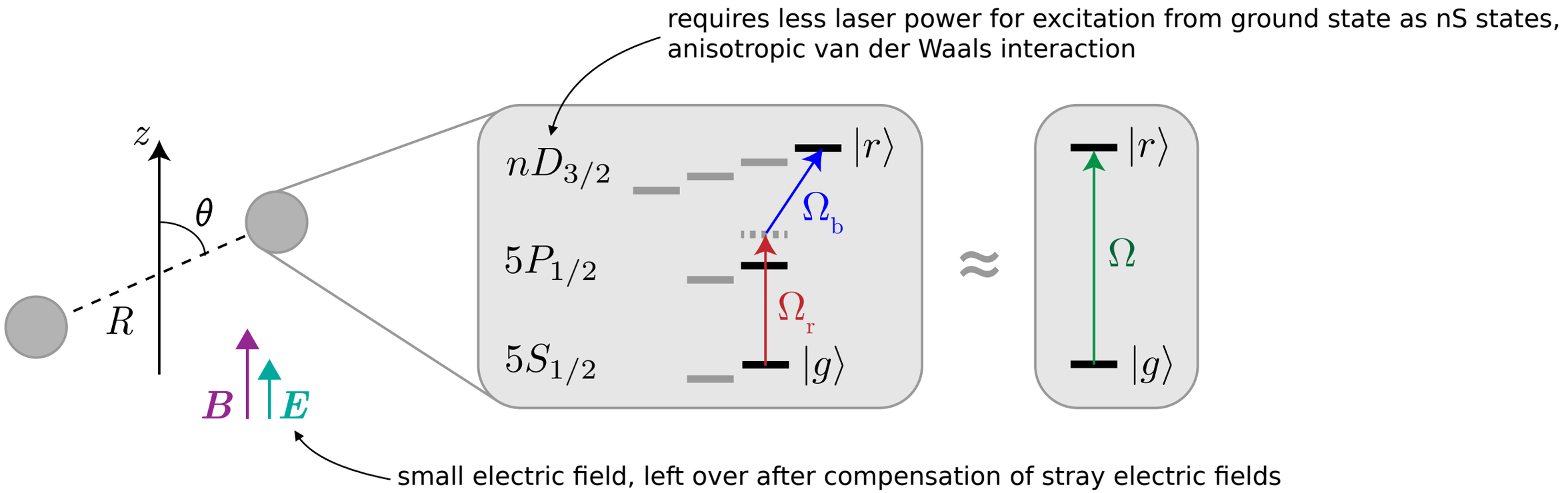
Basis size for 49 spin-1/2 particles: $2^{49} \approx 6 \cdot 10^{14}$

➡ direct numerical simulations intractable

M. Endres et al., Science **354**, 6315 (2016)

- **Requirement: accurate mapping of multilevel Rydberg atoms to spins with just a few levels**

Example: Ising-like system of spin-1/2 particles



We want to map the Rydberg atoms to spin-1/2 particles:

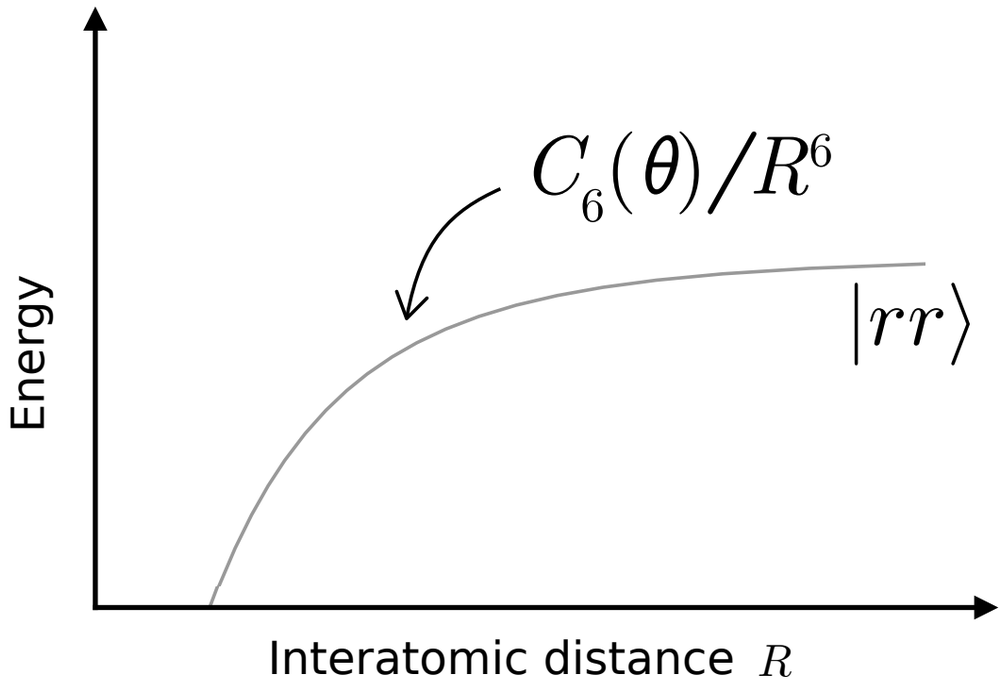
- $|g\rangle \rightarrow |\downarrow\rangle$, $|r\rangle \rightarrow |\uparrow\rangle$
- effective interaction between $|r\rangle_i$ and $|r\rangle_j$: U_{ij}

➡ $H = \sum_i \frac{\hbar\Omega}{2}\sigma_x^i + \frac{1}{2}\sum_{i\neq j} U_{ij} n_i n_j$ with $\sigma_x^i = |r\rangle\langle g|_i + |g\rangle\langle r|_i$, $n_i = |r\rangle\langle r|_i$

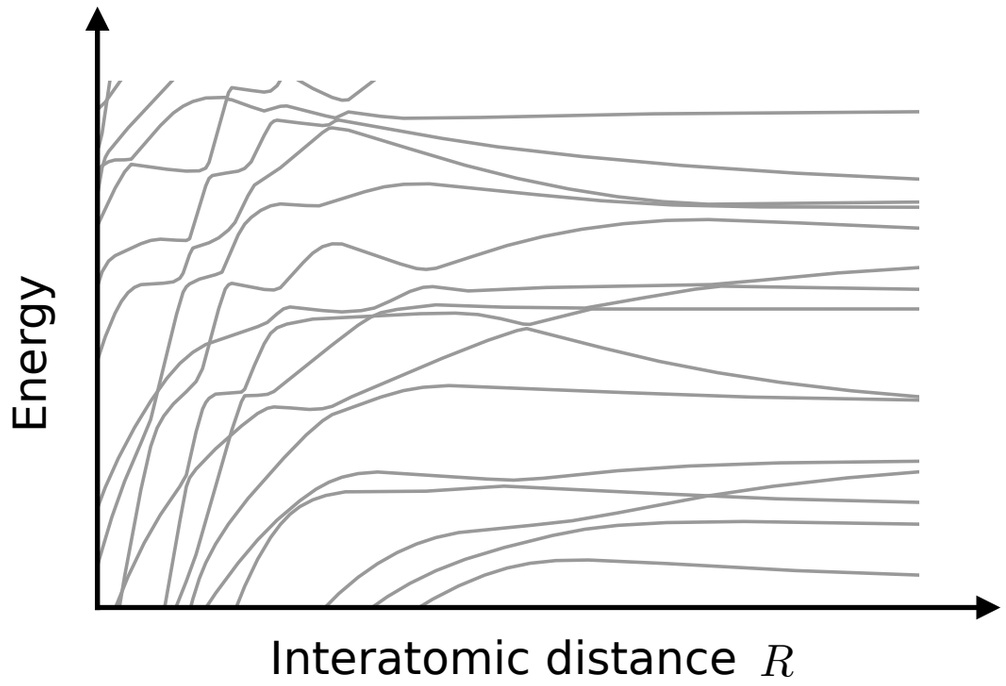
Ising-like model with transverse field

Example: Ising-like system of spin-1/2 particles

Ideal interaction potential



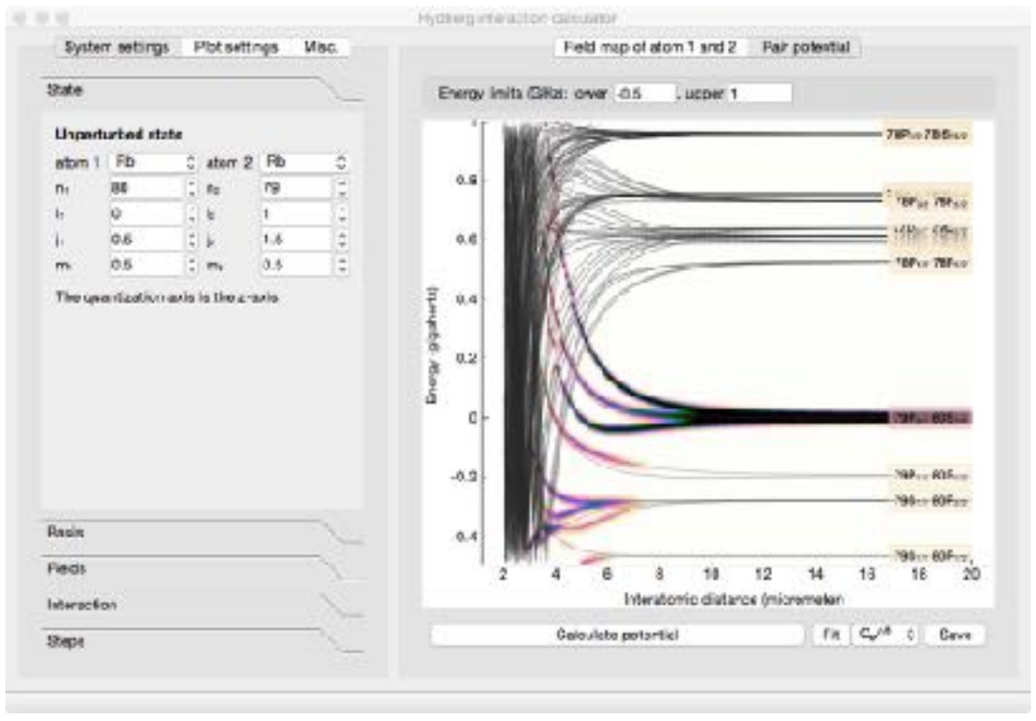
How reality looks like for generic experimental parameters



- ➡ Describing atoms as two-level systems is an approximation that can be difficult to fulfill
- ➡ Determination of suitable parameters requires calculation of Rydberg pair interaction potentials

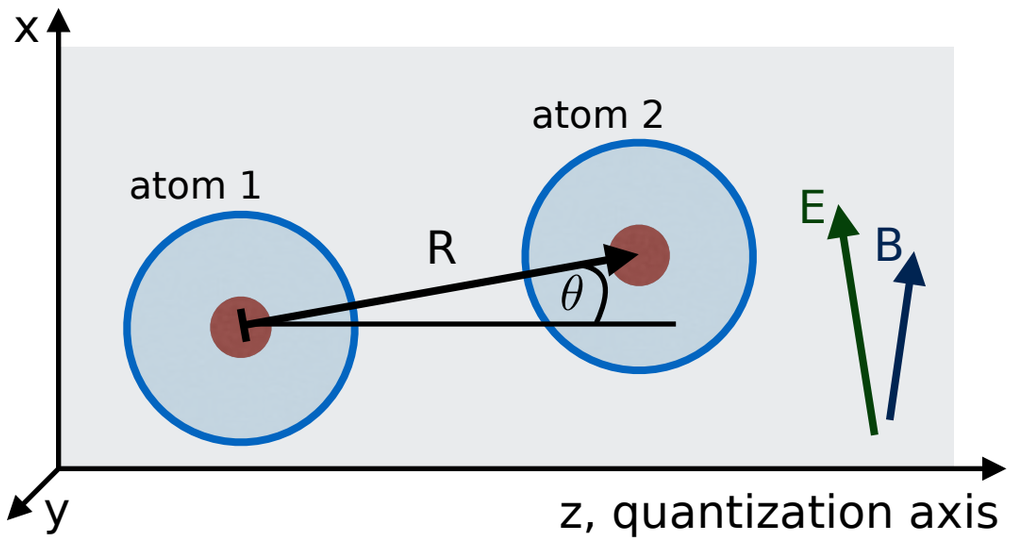
Non-perturbative calculation of Rydberg pair interaction potentials

J. Phys. B 50, 133001 (2017)



Pair potential calculation

Step 1: set up the Hamiltonian



- Born–Oppenheimer approximation
- R > Le Roy radius
  - ➡ multipole approximation, no exchange interaction
- R < wavelength of Rydberg-Rydberg transitions
  - ➡ no retardation effects

$$H = (H_{\text{atom1}} + H_{\text{atom1-fields}}) \otimes \mathbb{1} + \mathbb{1} \otimes (H_{\text{atom2}} + H_{\text{atom2-fields}}) + H_{\text{multipole interaction}}$$

energies of unperturbed Rydberg states

interaction with static E and B-fields

interaction between the two Rydberg atoms

Pair potential calculation

Step 2: define the basis

Full basis set:

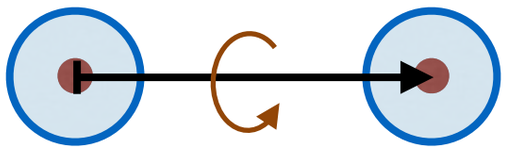
Set of all pair states $|n_1, l_1, j_1, m_{j1}\rangle \otimes |n_2, l_2, j_2, m_{j2}\rangle$

Restricted basis set:

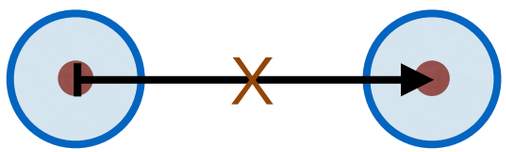
If interested in the pair potential of the pair state $|\psi\rangle$, restrict basis to states with ...

- similar *energy* as $|\psi\rangle$
- similar *principal and momentum quantum number* as $|\psi\rangle$
- same *symmetry* as $|\psi\rangle$

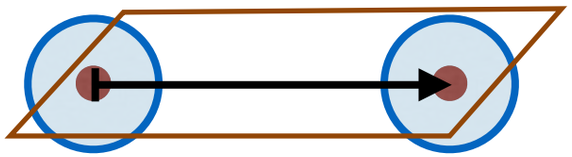
Rotation: $m_{j1}+m_{j2}$ conserved



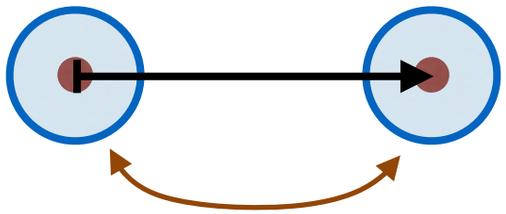
Inversion



Reflection



Permutation (if no interaction of higher order than dipole-dipole)



Pair potential calculation

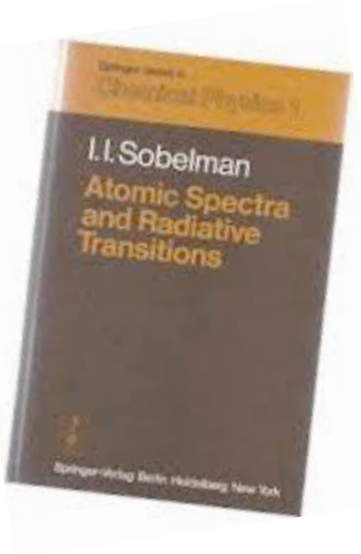
Step 3: diagonalize the Hamiltonian within the basis

$$\begin{pmatrix} \langle b_1|H|b_1\rangle & \langle b_1|H|b_2\rangle & \cdots \\ \langle b_2|H|b_1\rangle & \langle b_2|H|b_2\rangle & \cdots \\ \vdots & \vdots & \ddots \end{pmatrix}$$

where $|b_i\rangle$ are basis elements

Calculate matrix elements $\langle b_i|H|b_j\rangle$

- decompose into single atom matrix elements
- radial and angular part separate
  - radial matrix elements: radial Schrödinger equation
  - angular matrix elements: Wigner-Eckart theorem



Diagonalize the Hamiltonian matrix

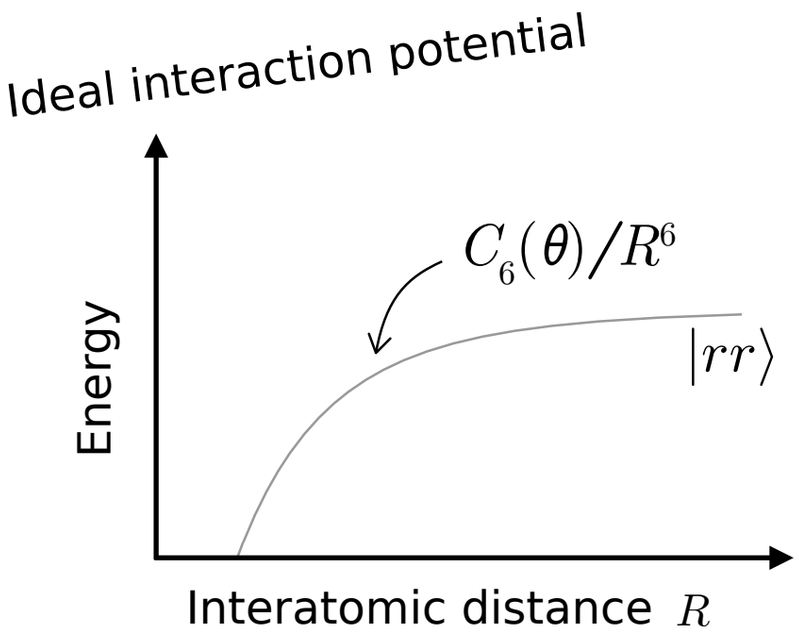
➡ eigen energies plotted as a function of the interatomic distance make up the pair potentials

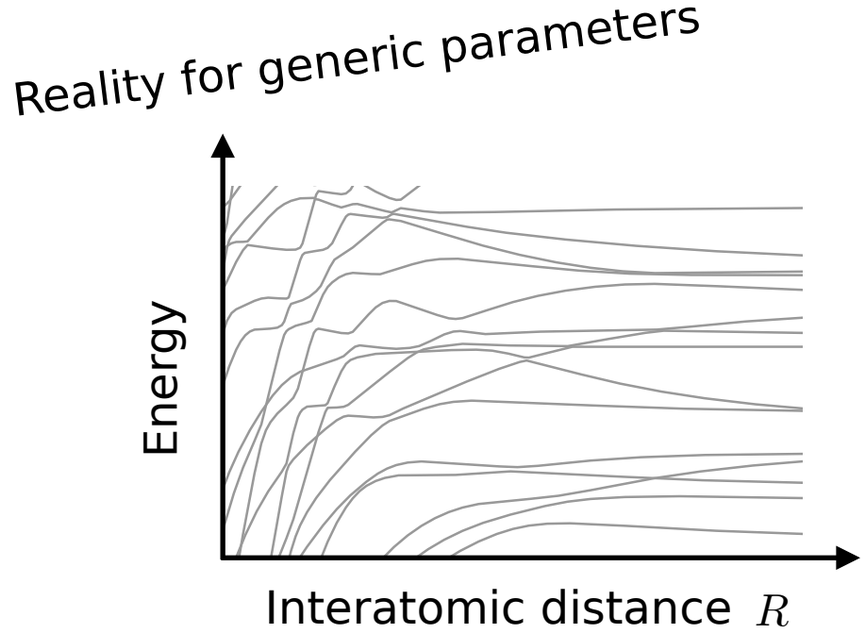
Our *Pairinteraction* software is available as open-source: https://pairinteraction.github.io

Similar open-source project by Nikola Šibalić et al.: https://github.com/nikolasibalic/ARC-Alkali-Rydberg-Calculator

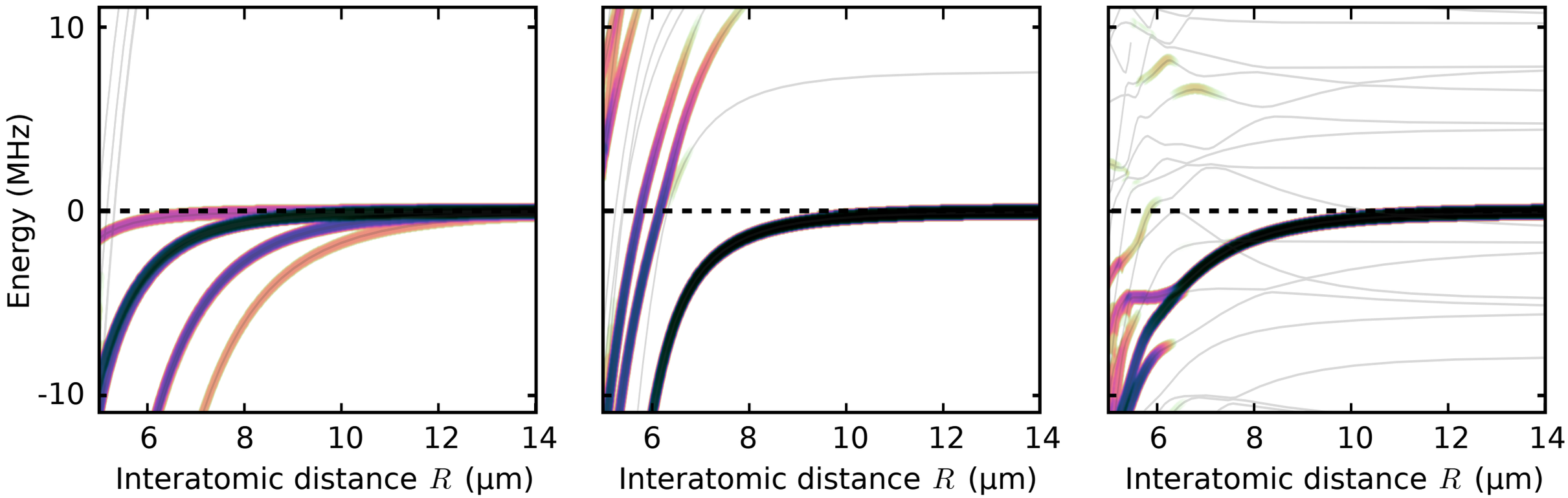
Usage of pair interaction potentials for the determination of optimal parameters

arXiv:1710.06156 (2017)





Influence of B-fields on pair potentials



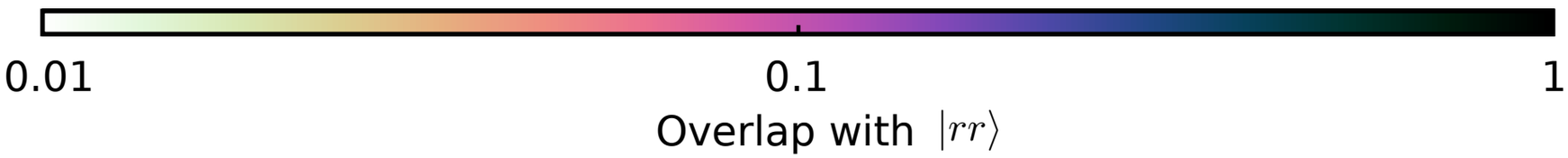
Degenerate Zeeman levels

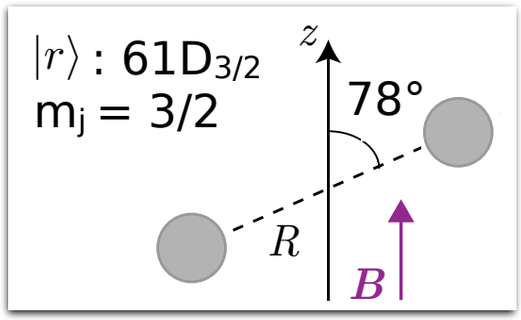
T. G. Walker and M. Saffman, Phys. Rev. A **77**, 032723 (2008)

Crossing Zeeman levels

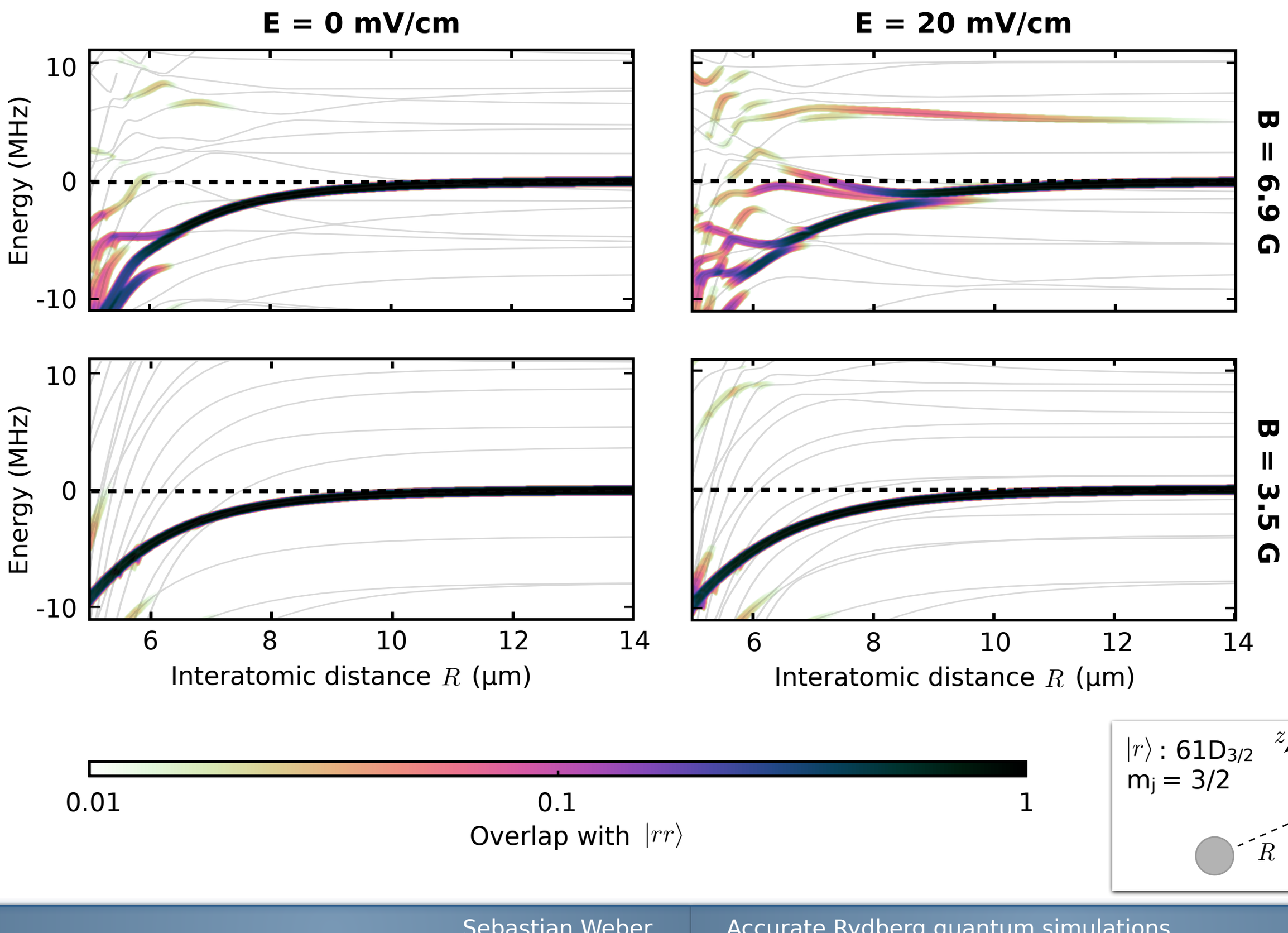
B. Vermersch et al., Phys. Rev. A **91**, 023411 (2015)

Reasonable Rydberg blockade

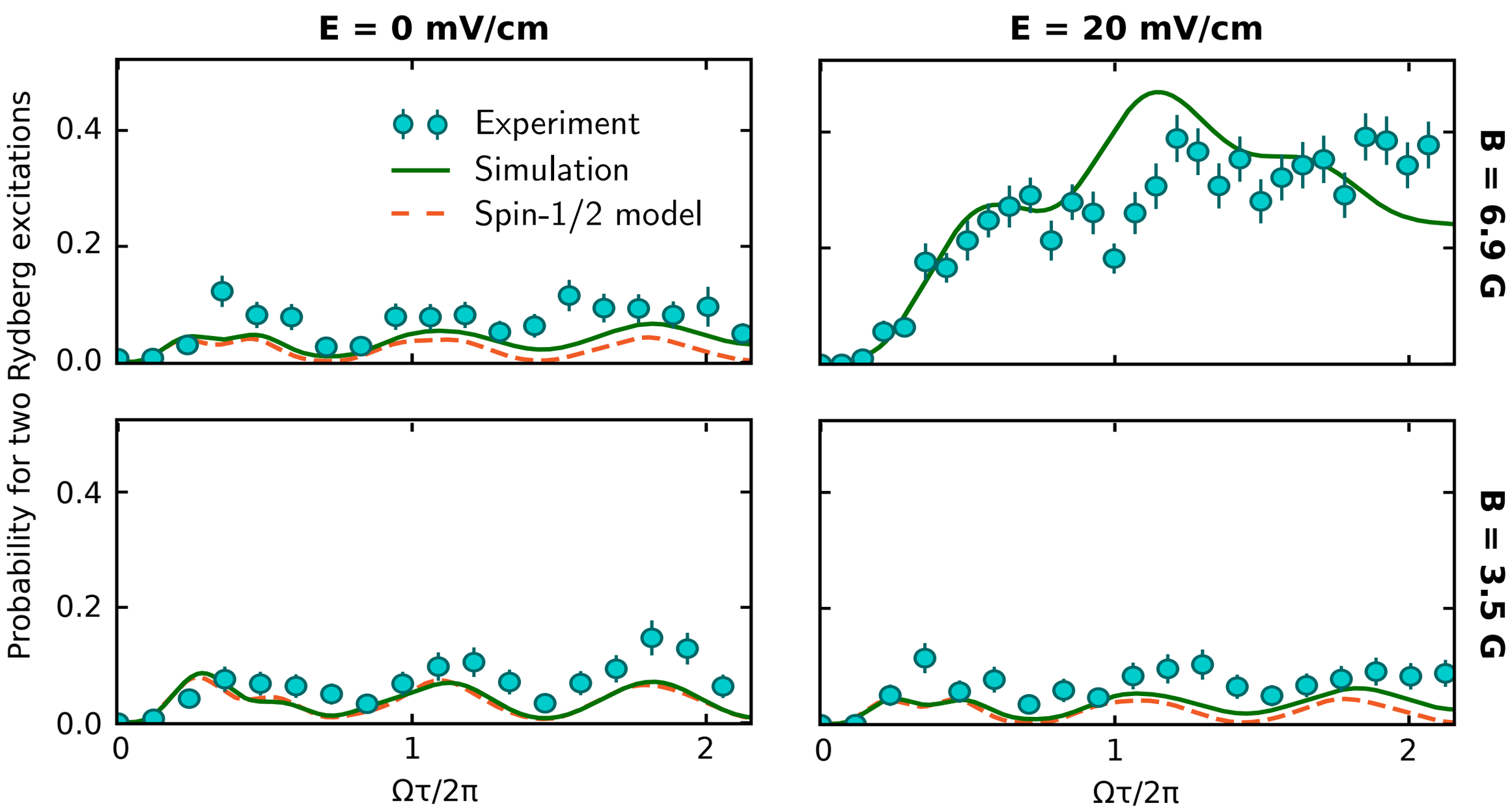




Influence of an additional small E-field



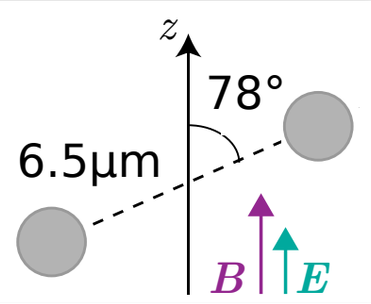
Experimental test of the predictions



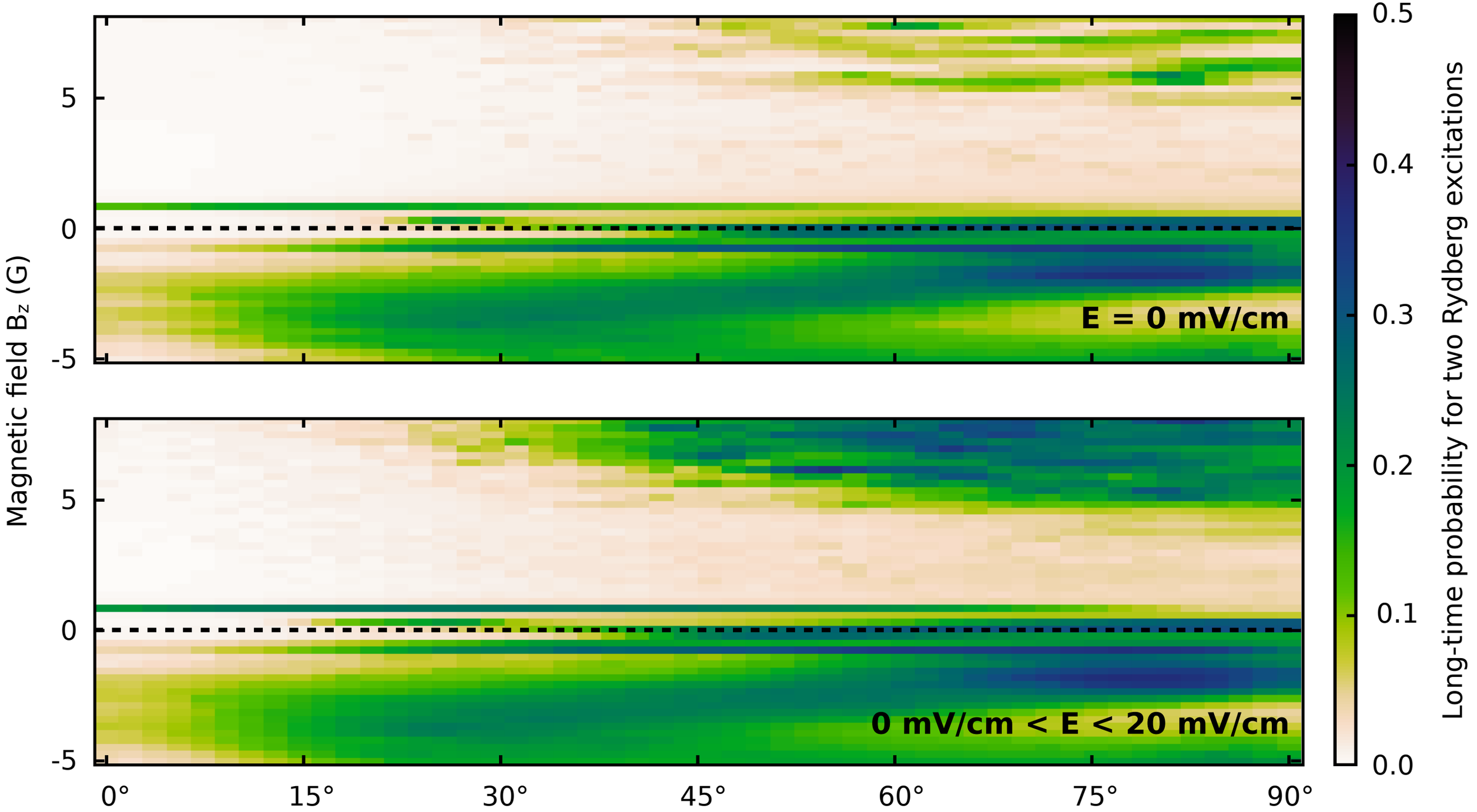
Predicted breakdown of Rydberg blockade experimentally seen as increasing probability for two Rydberg excitations

$|r\rangle$: $61D_{3/2}$
$m_j = 3/2$

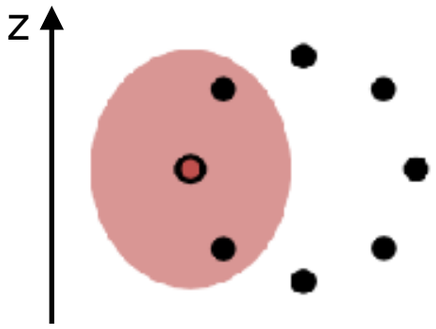
$\Omega = 2\pi \cdot 1.2\text{MHz}$



Influence of geometry

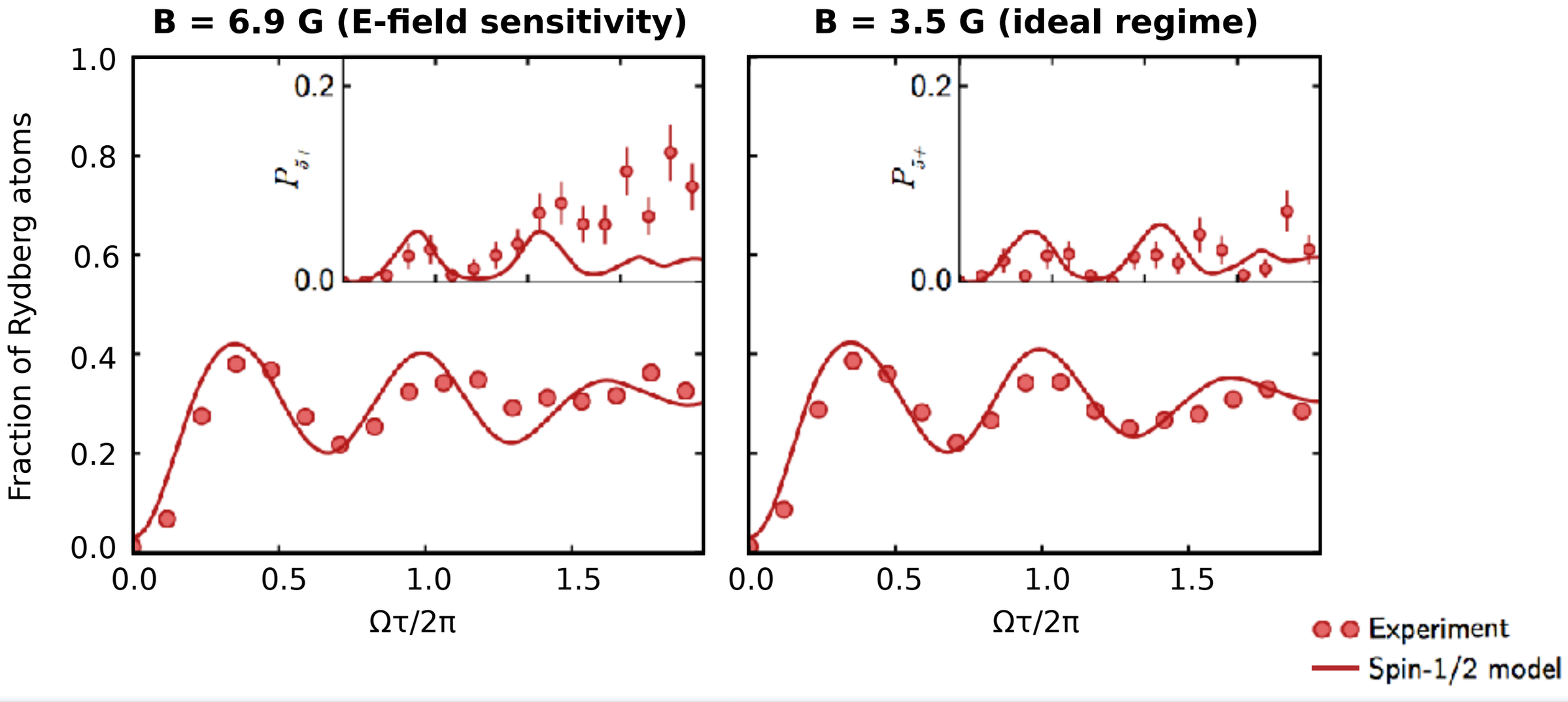


Quantum simulation of a 8-atom ring

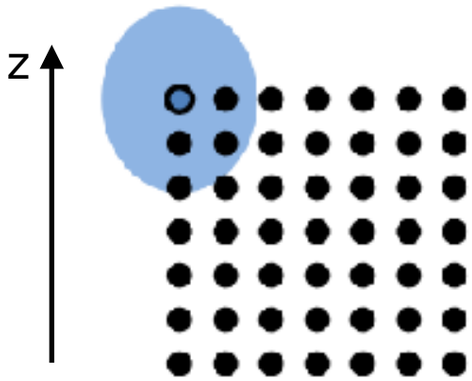


Prior to the experiment, stray electric field compensated better than 5 mV/cm

Revisit of the experiment reported in H. Labuhn et al., Nature **534**, 667 (2016)



Quantum simulation of a defect-free 7x7 lattice



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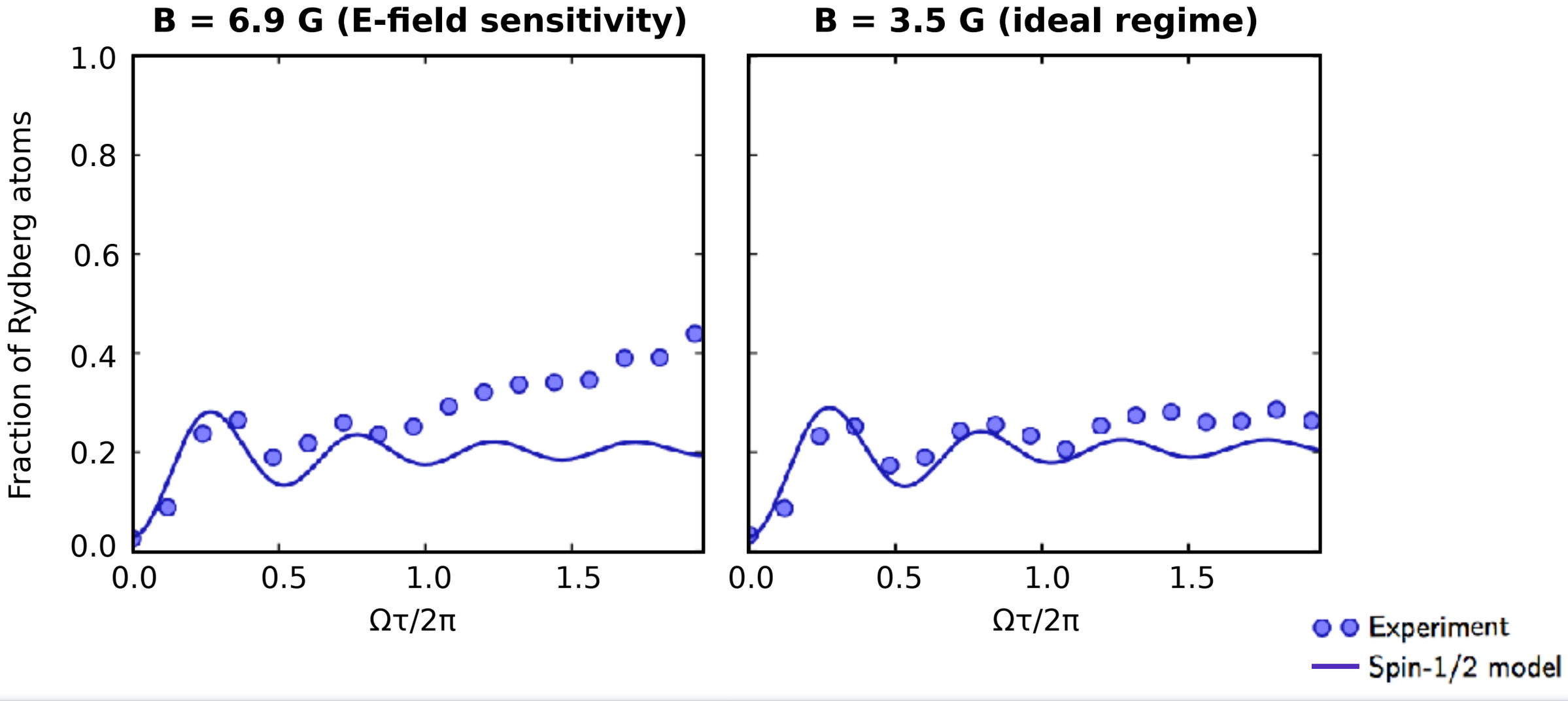
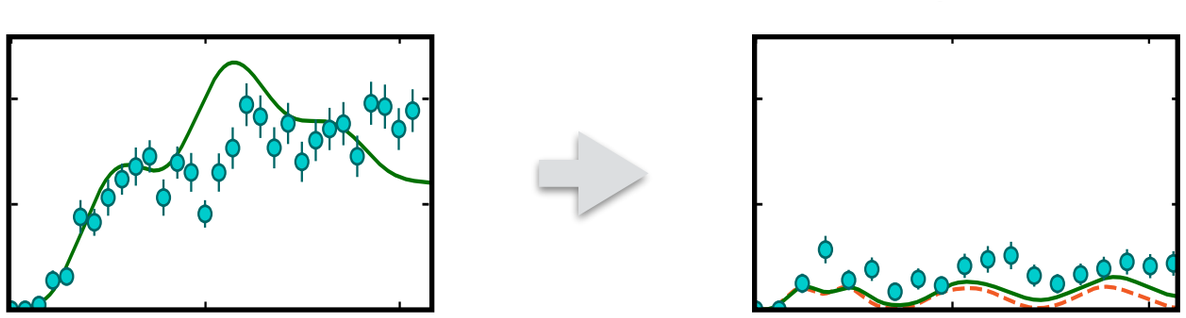


Conclusion

- E-field sensitivity of Rydberg blockade for D states, resolved by tuning the B-field

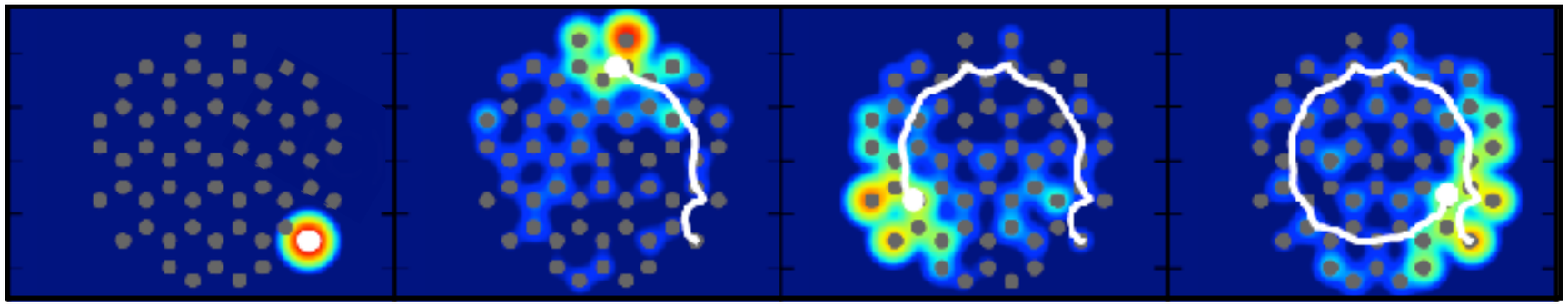
- Predictions verified in 2-atom blockade experiments



- Increased accuracy of Rydberg quantum simulations

Outlook

- Optimize further parameters
- Use optimization procedure for other experiments
- Investigate mapping to dipolar interacting spin-1 particles, e.g. useful for realizing topological bands



Details on ...

- pair potential calculations: J. Phys. B **50**, 133001 (2017)
- optimization of mapping to spin-1/2 particle: arXiv:1710.06156 (2017)