RYDBERG QUANTUM SIMULATOR
RYSQ

PIs AND INSTITUTION INVOLVED

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Robert Spreeuw – Universiteit van Amsterdam

Guido Pupillo – Université de Strasbourg

Matthias Weidemüller – Universität Heidelberg

Ferdinand Schmidt-Kaler – Universität Mainz

Hans Peter Büchler – Universität Stuttgart

Klaus Mølmer/David Petrosyan – Aarhus University

Igor Lesanowsky – Nottingham University

Tommaso Calarco – Universität Ulm

Servaas Kokkelmans– Technische Universiteit Eindhoven

Oliver Morsch – Istituto Nazionale di Ottica

Thomas Pohl– Max Planck Institute Complex Systems

... „Gentlemen's agreement"

COORDINATION

Tommaso Calarco – Universität Ulm

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Steering Committee

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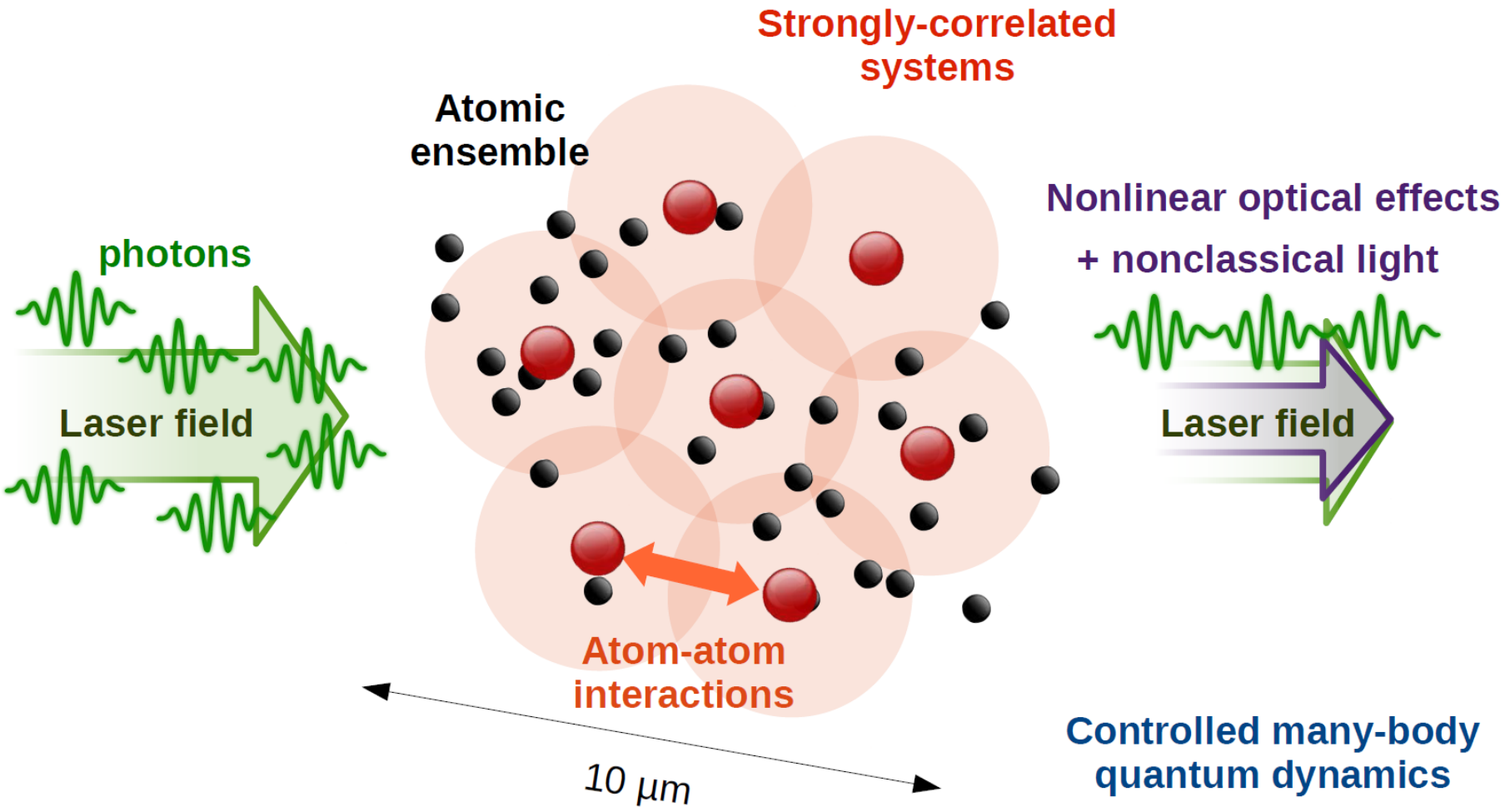
Klaus Mølmer – Aarhus University

Matthias Weidemüller – Universität Heidelberg

Peter Zoller – ÖEAW

PROJECT STRUCTURE

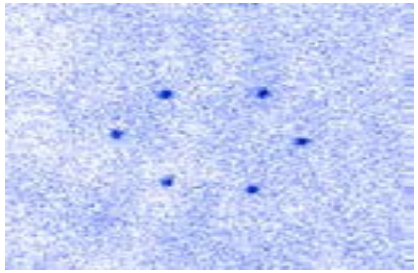
- **PLATFORMS**
  - Atoms
  - Ions
- **SCIENTIFIC QUESTIONS**
  - Few-body physics
  - Many-body physics
- **APPLICATIONS**
  - Non-equilibrium dynamics
  - Quantum magnetism
  - Soft matter
  - Biological systems


Strongly-correlated systems
Atomic ensemble
photons
Laser field
Nonlinear optical effects
+ nonclassical light
Laser field
Atom-atom interactions
10 μm
Controlled many-body quantum dynamics

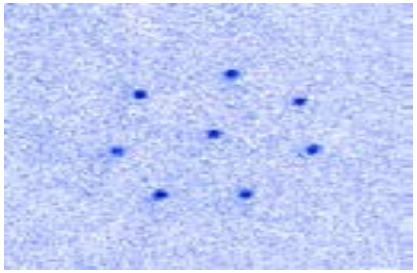
Max Planck Institute - Garching

Controlled Excitation Via Sweeps

Large 2D ordered states

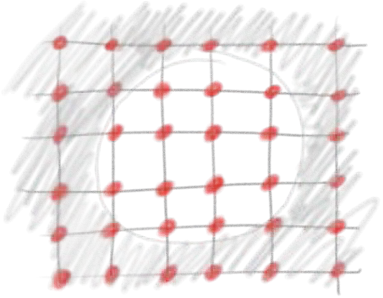


6 Rydberg atoms

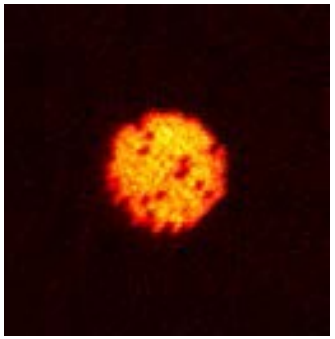


8 Rydberg atoms

Precise initial state control



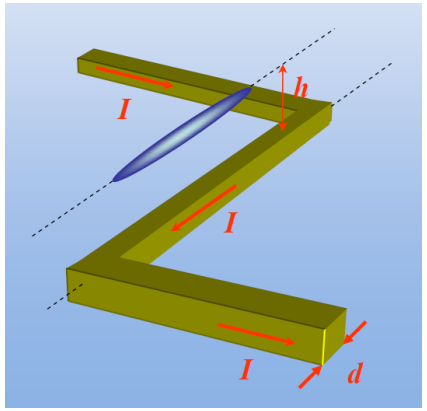
DMD cleanup



An atom cookie

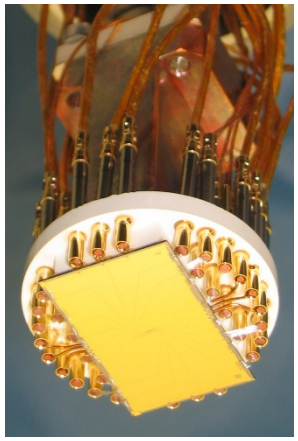
Atom chips

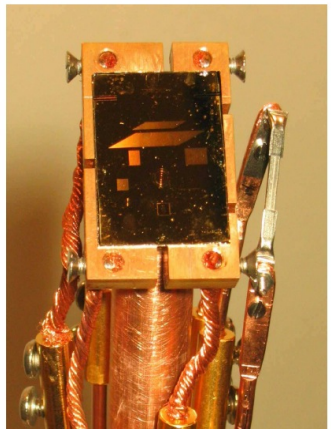
Generic Z-wire

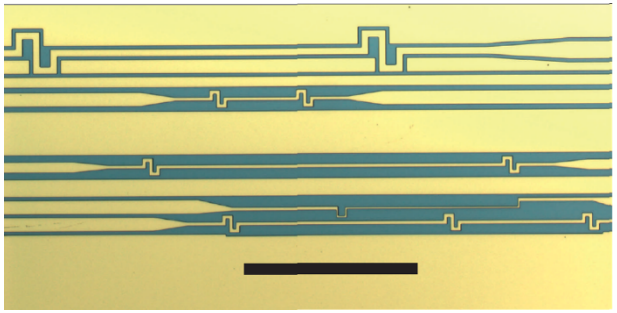


wires

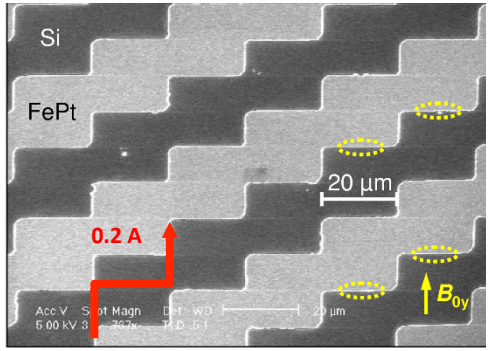
perm. magnet





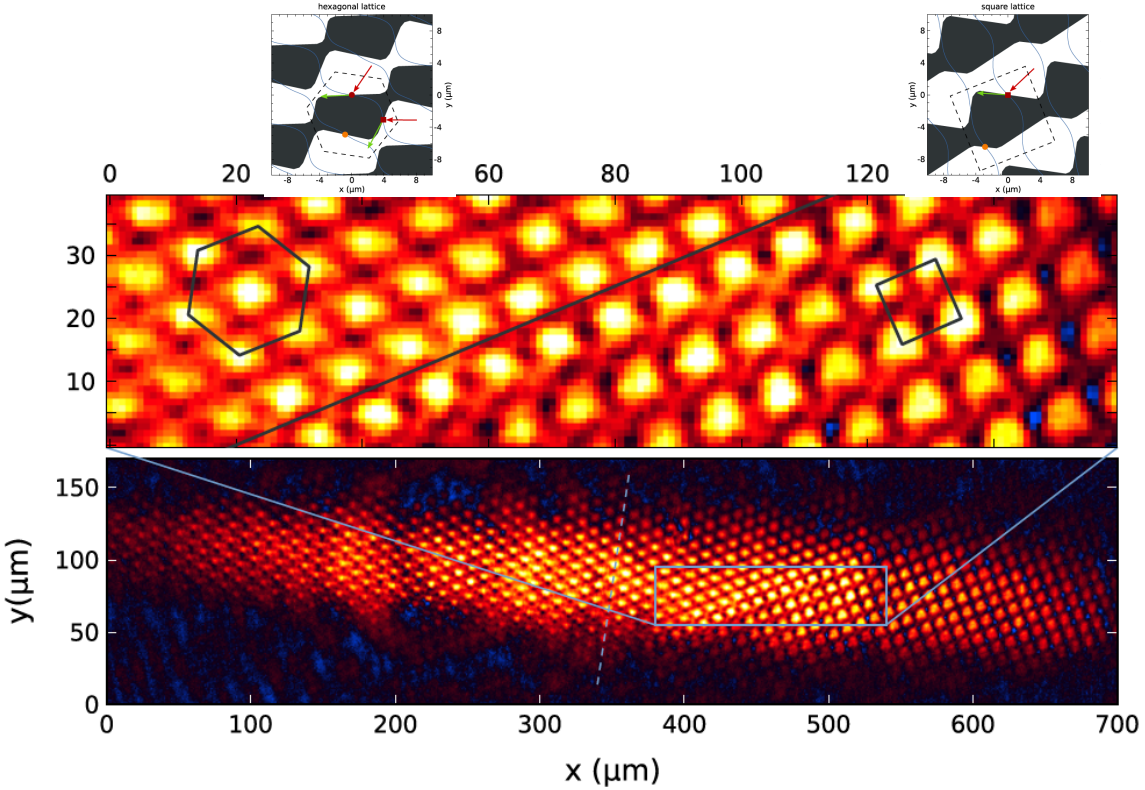


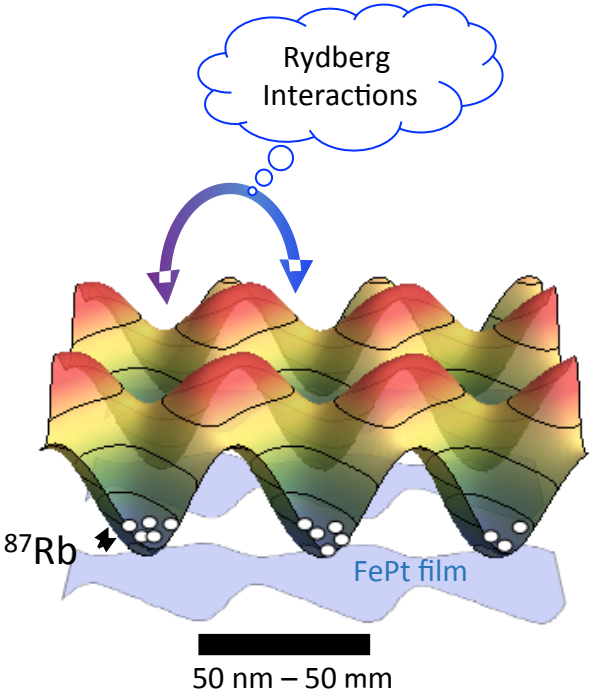
One-dimensional quantum gas
(N.J. van Druten)



Two-dimensional lattices
(R.S.)

2D magnetic lattices on an atom chip





- Lattice constant compatible with Rydberg interaction
- Different geometries, length scales
- Designer defects, disorder, non-periodic structures,…
- Single atoms or ensemble qubits
- Tight magnetic traps (10kHz-MHz), Ioffe-Pritchard type
- Rydberg atoms near surfaces

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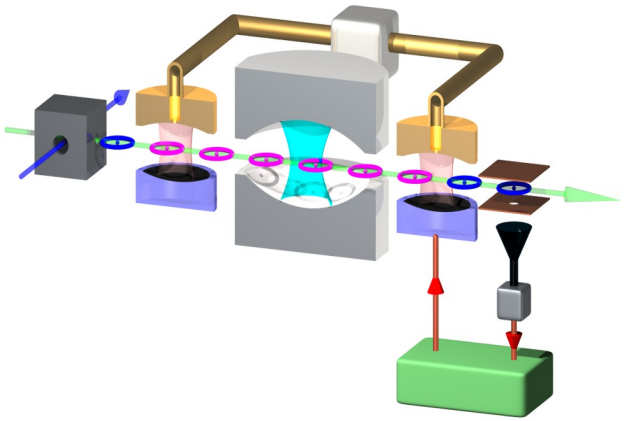
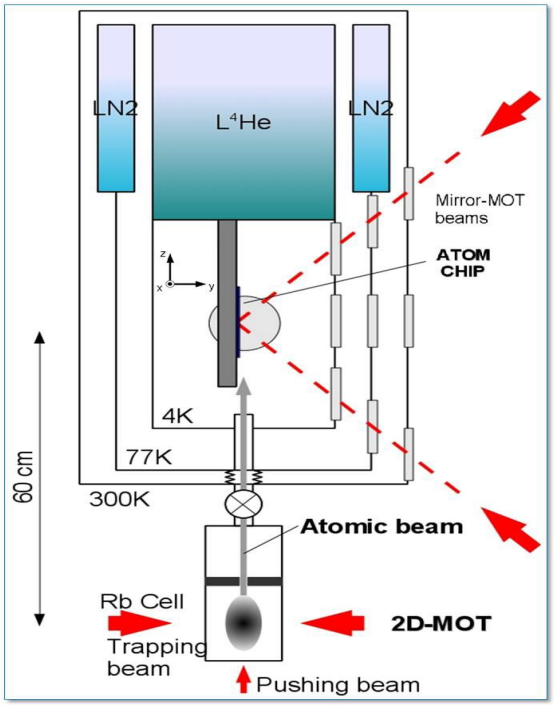
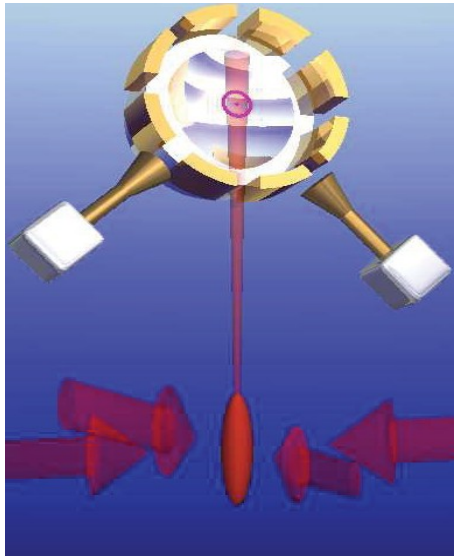
QND measurement



Superconducting atom chip



Stationary atom



Durham University

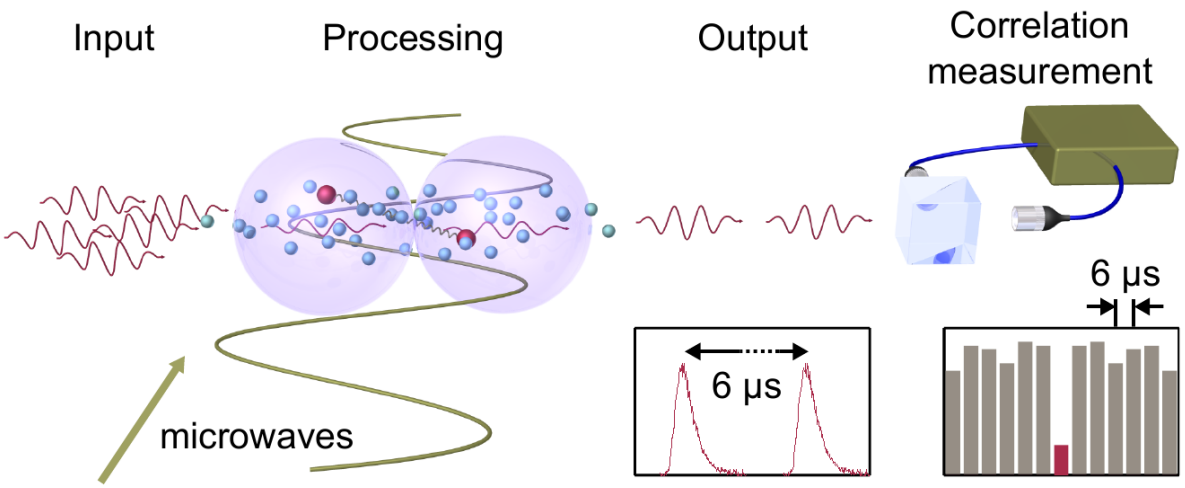
All-optical Rydberg quantum simulator

Methodology

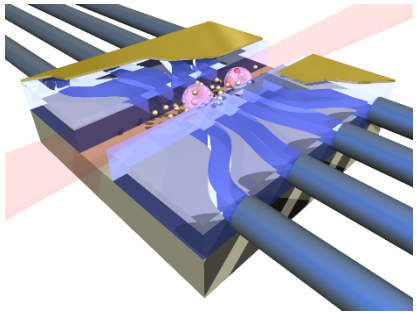
Rydberg quantum memory

Process

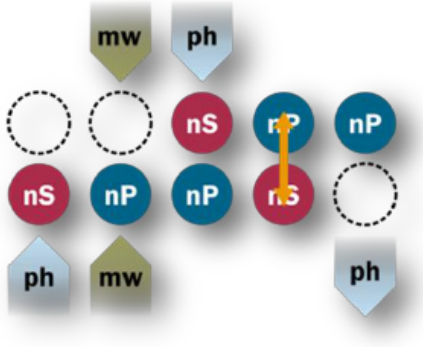
Stored optical field



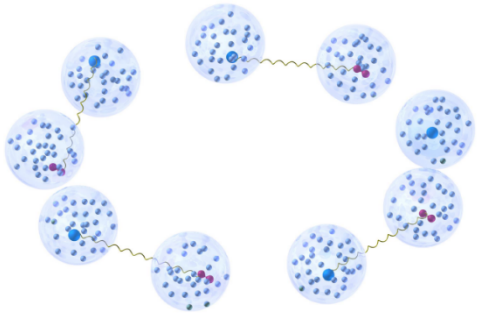
On-chip architecture



What can we simulate?



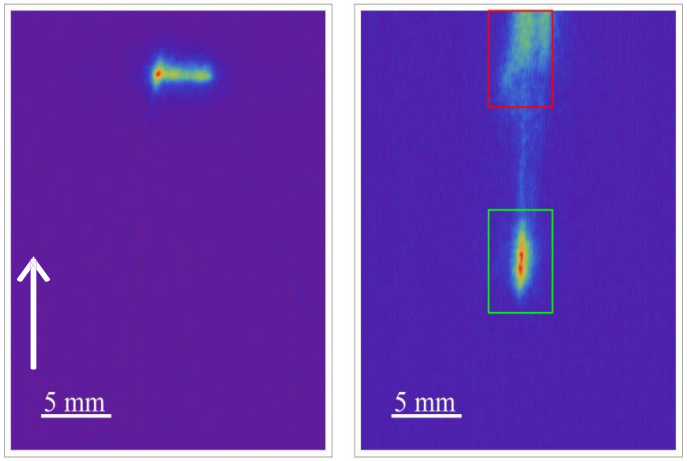
Controlled photon hopping

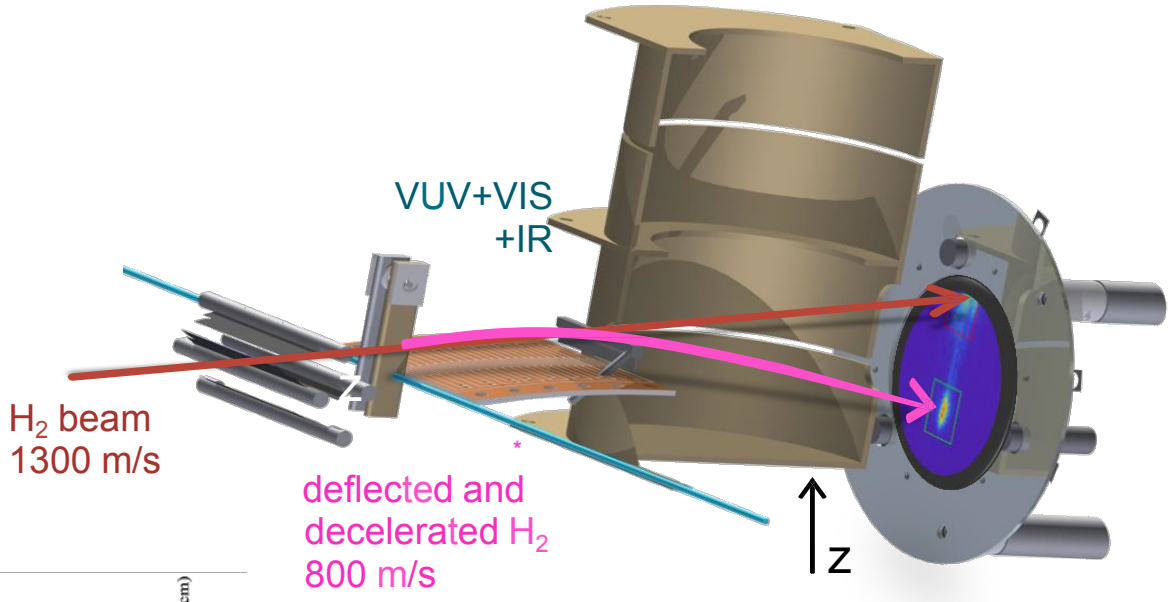


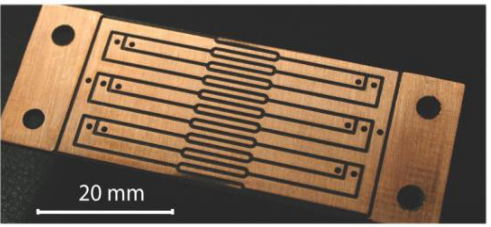
Resonant energy transfer

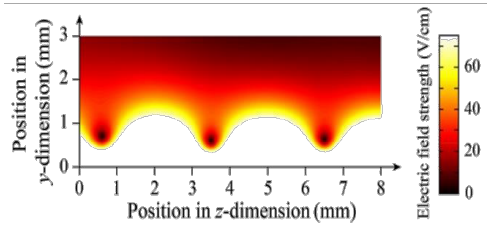
Guiding and deceleration of Rydberg molecules

- supersonic expansion of pure H_2 at LN_2 temperatures
- 3-photon excitation into molecular Rydberg states with *M*=3
- guiding, deceleration, and deflection using a chip based decelerator *
- ➢ coupling Rydberg atoms to superconducting qubits – towards a hybrid atom-semiconductor device



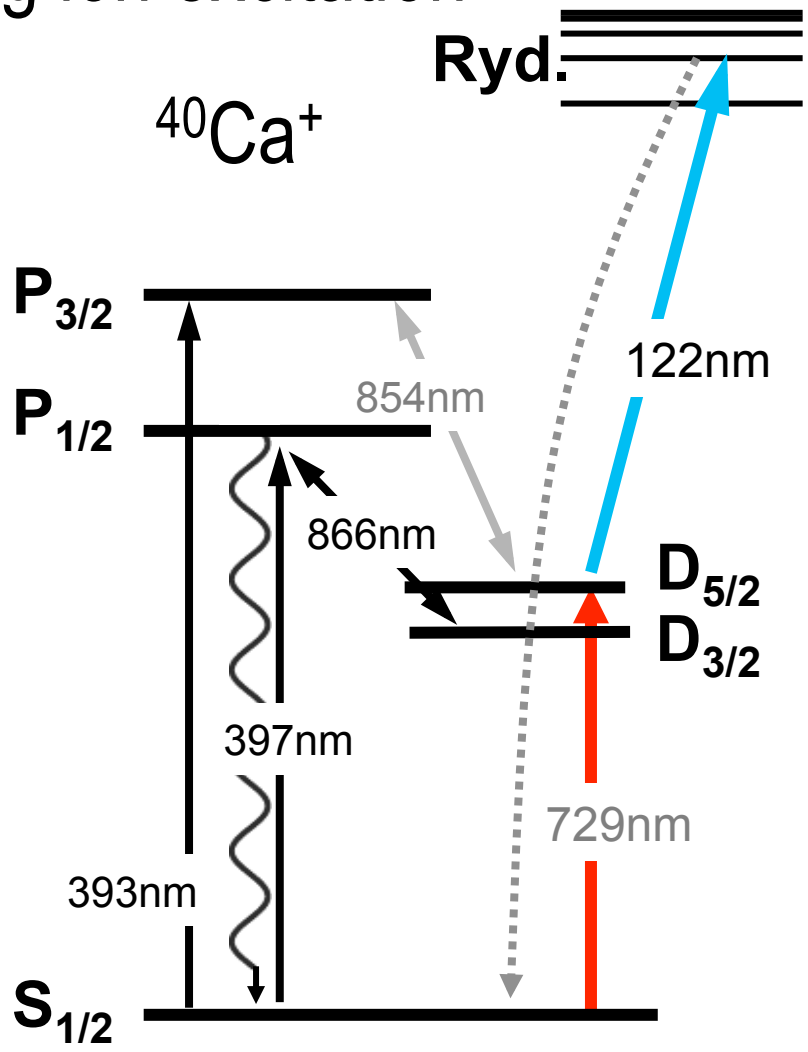




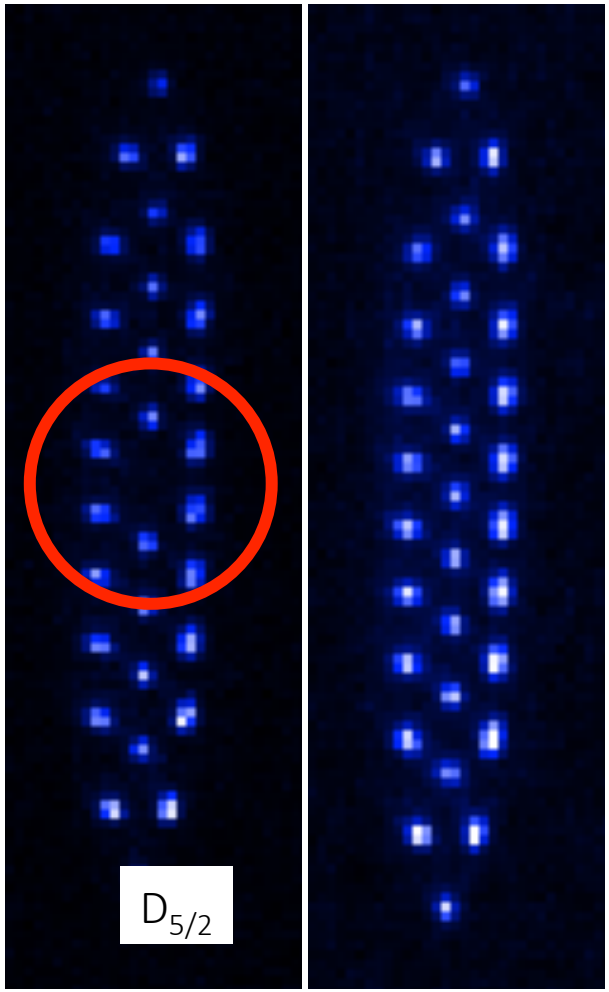


(*) see e.g. P. Allmendinger *et al., Phys. Rev. A* **88(4)**, 043433 (2013)

Rydberg ion excitation

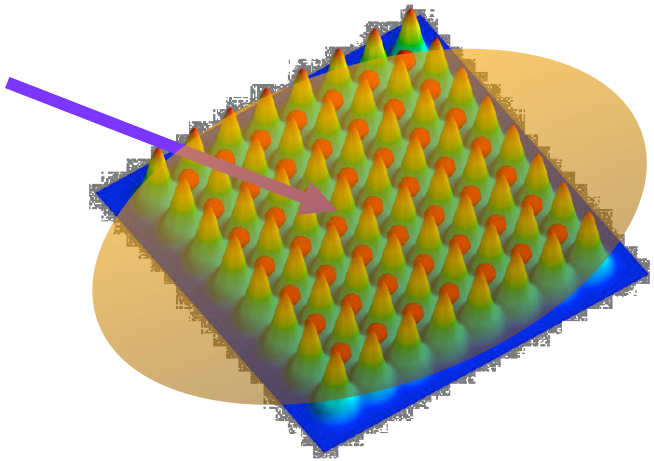


scheme

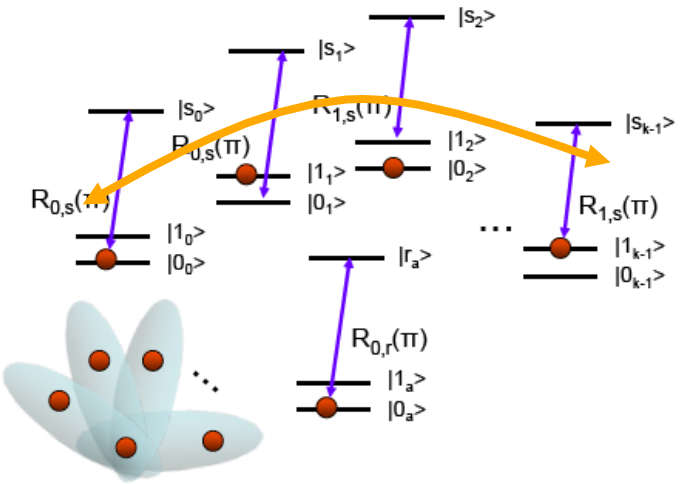


single site addressing in planar crystal

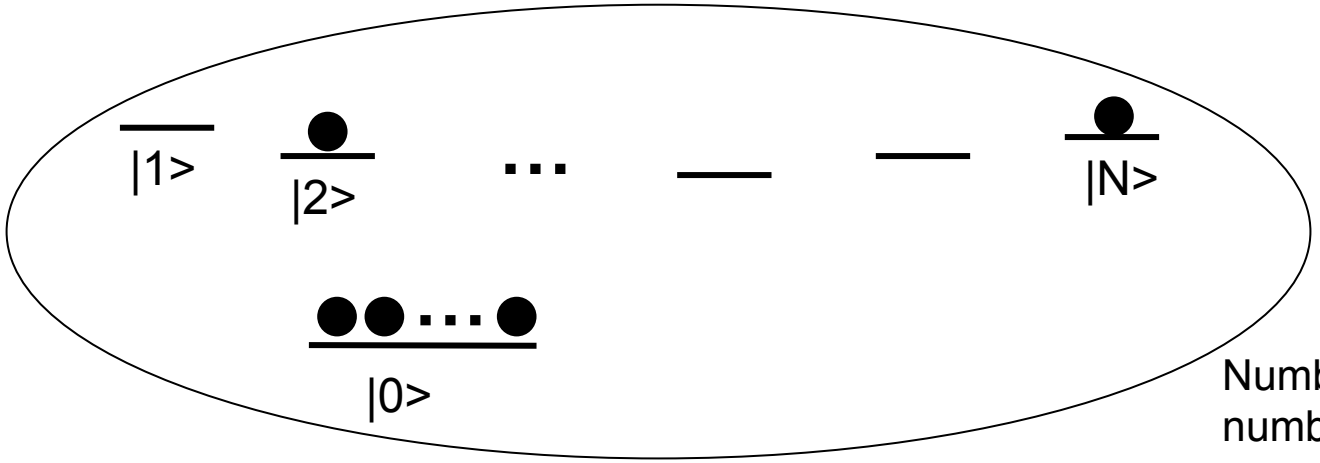
Multi-atom encoding and algorithms



Multi-qubit conditional gates and algorithms (C^k-NOT and Grover)



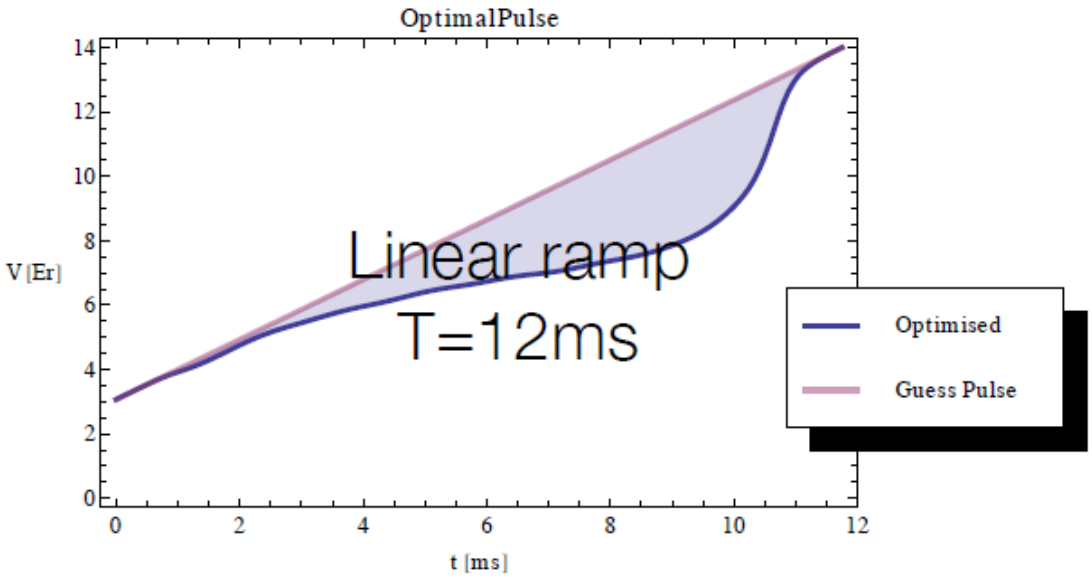
Collective encoding in internal (external) states



Number of bits ~
number of states (linear scaling)!!!

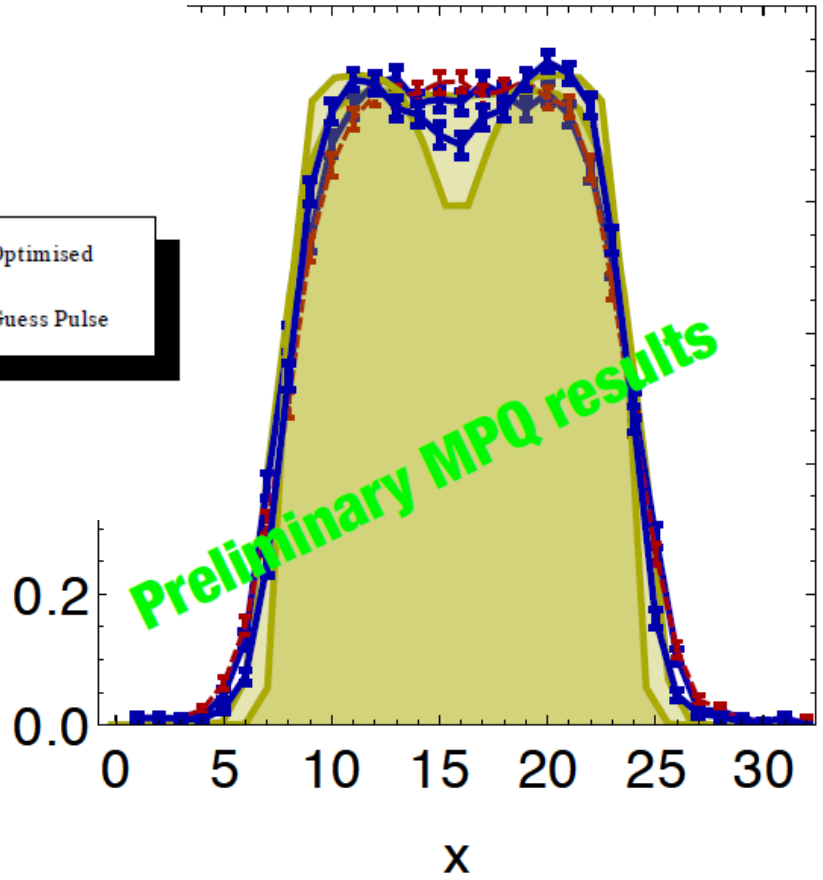
Optimal control of quantum phase transitions

- Suppressing defects in the Mott transition



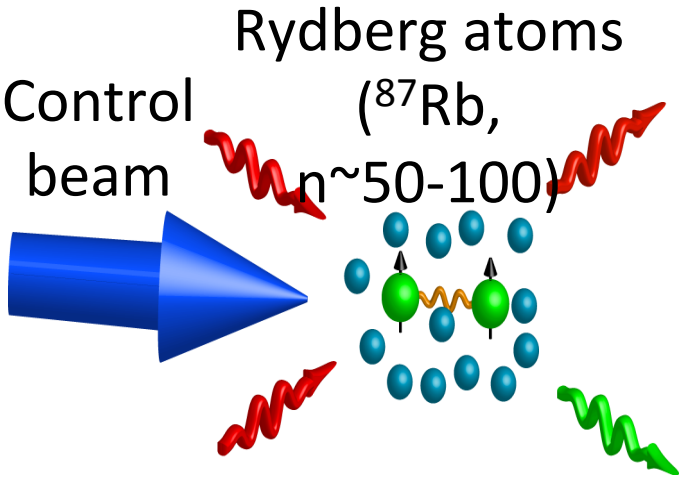
Adiabatic ramp
T=110ms

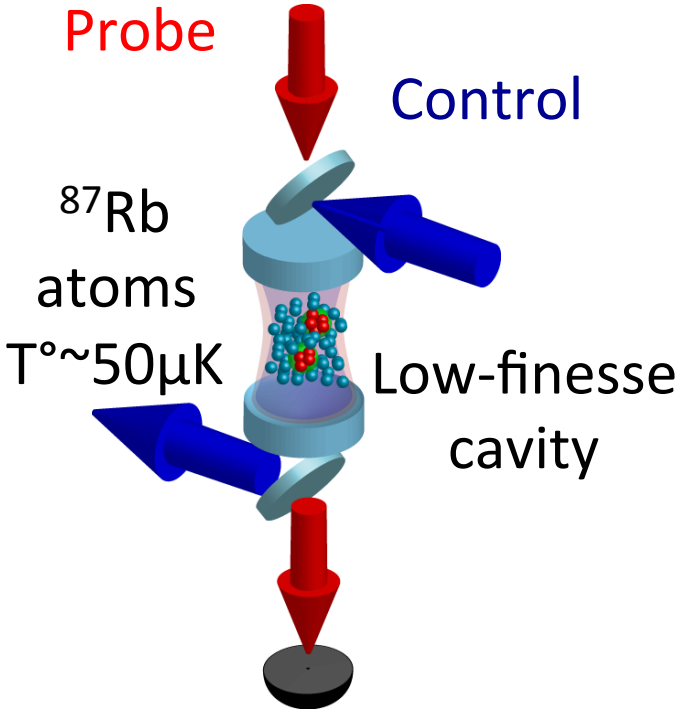
Optimal ramp
T=12ms



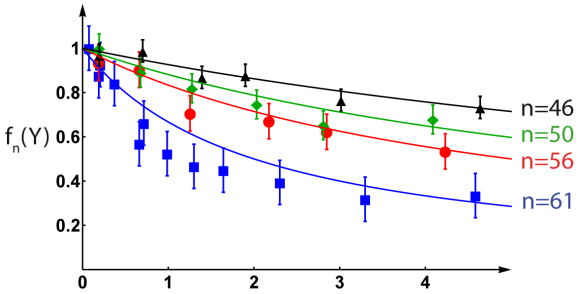
Istitute d'Optique

Photonic interactions in a Rydberg gas



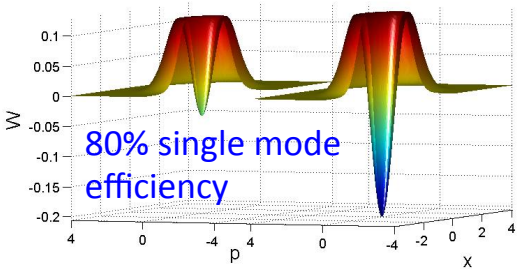


Large interaction-induced non-linearities



- Parigi *et al*, PRL **109**, 233602 (2012)
- Stanojevic *et al*, PRA **88**, 053845 (2013)

Creation of heralded single-mode photons

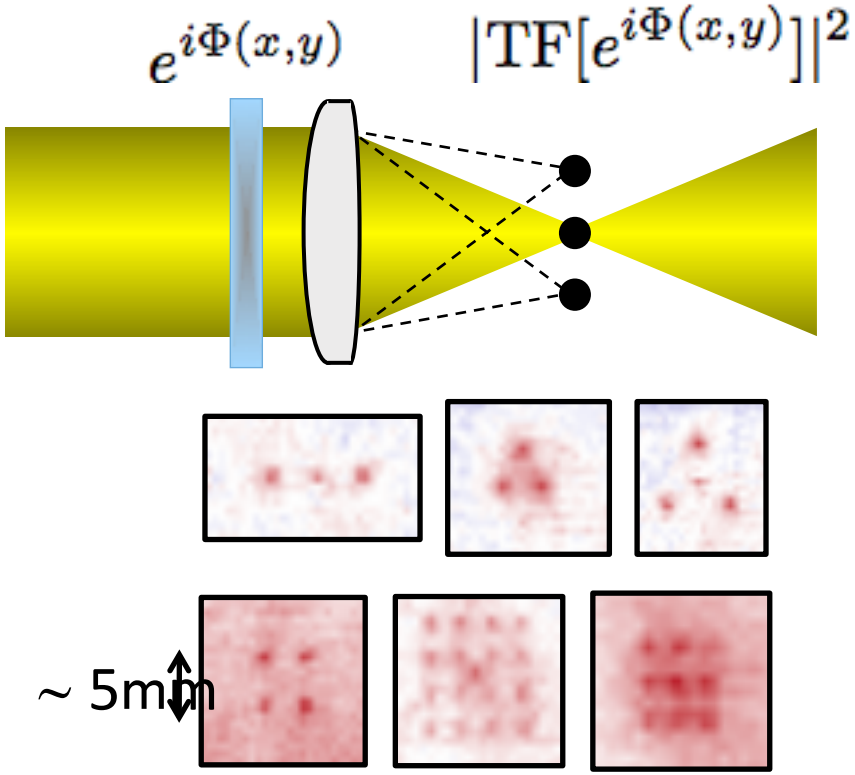


- Bimbard *et al*, PRL in press
- Stanojevic *et al*, PRA **84**, 053830 (2011)

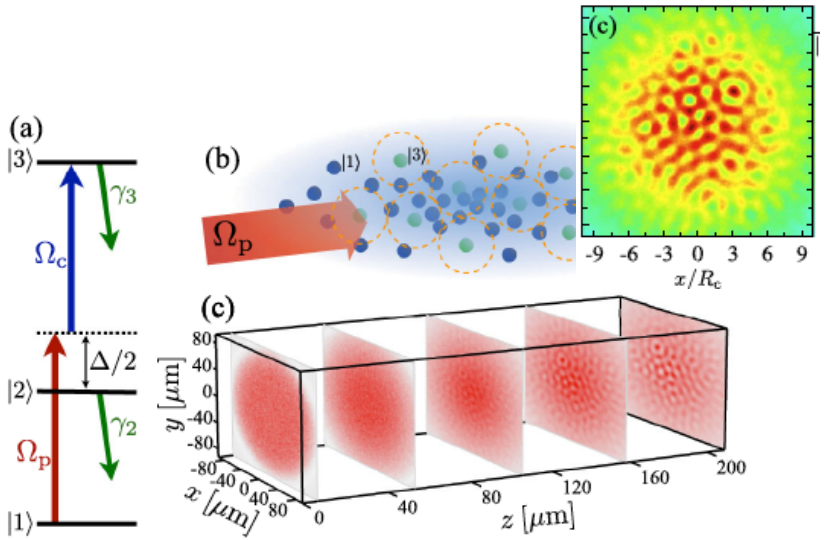
- Stanojevic *et al*, PRA **86**, 021403(R) (2012)
- Grankin *et al*, submitted to NJP

Istitute d'Optique

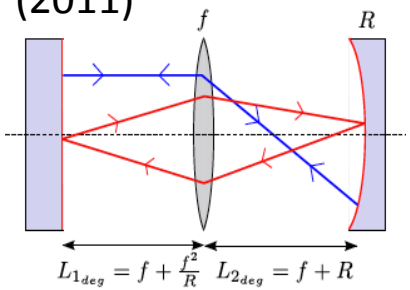
Arrays of Rydberg atoms



Ensemble of Rydberg atoms inside a multimode cavity



T. Pohl et al, "Non-local non-linear optics in cold Rydberg gases", PRL 107, 153001 (2011)



Self-imaging cavity (multimode & degenerate)

Use controlled interaction to

1.Entangle ~ 10 atoms
(ok for 2, PRL 2010 & PRL 2013)

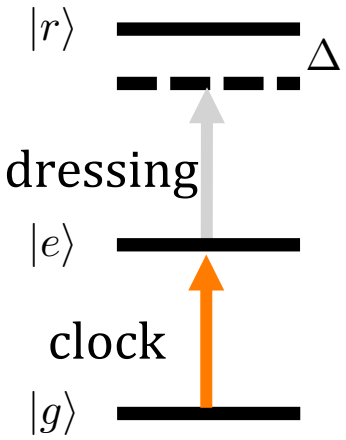
2. Simulate many-body quantum system

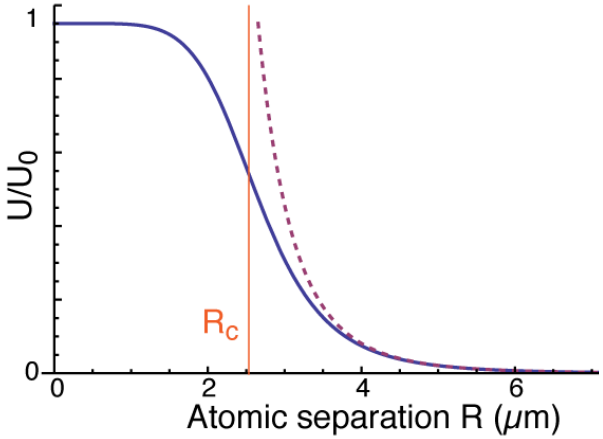
Explore « quantum fluids of light »

Lattice clock Rydberg quantum simulator

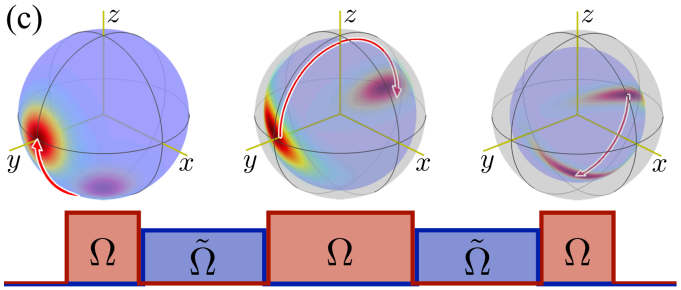
Methodology

Metastable states for Rydberg dressing

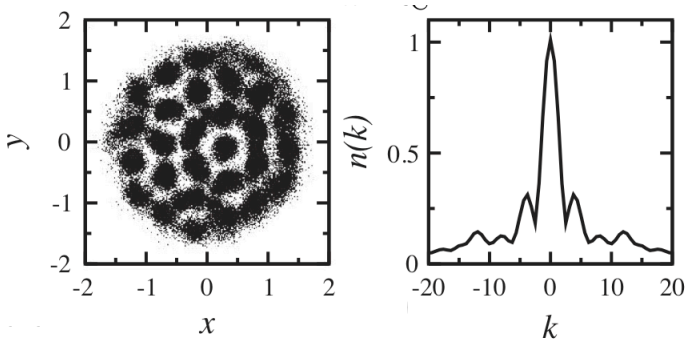




What can we simulate?



Lattice spin models e.g $\hat{H} \propto \hat{J}_x^2$ quantum metrology



F. Cinti et al., Phys. Rev. Lett. **105**, 135301 (2010)

Rydberg supersolids

Collaboration with T. Pohl (Gil et al. arXiv/1306.6240)

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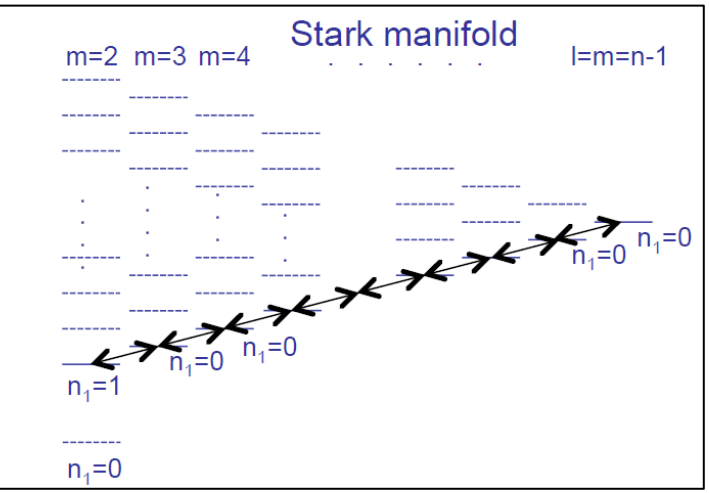
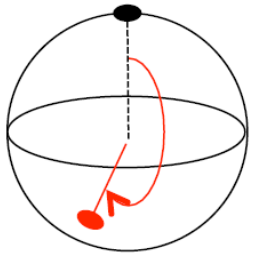
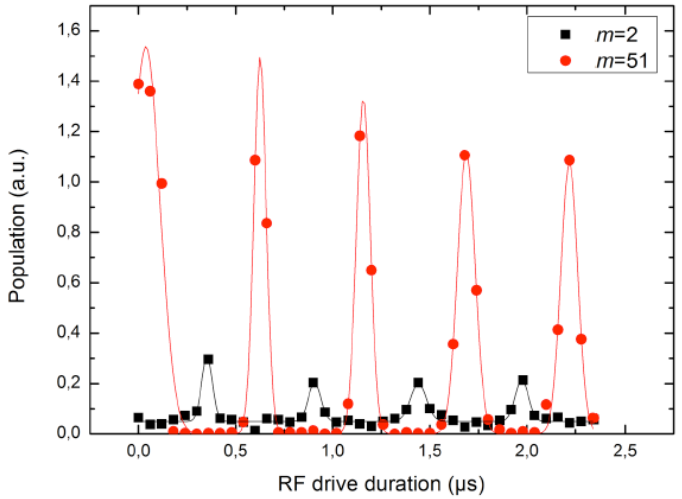
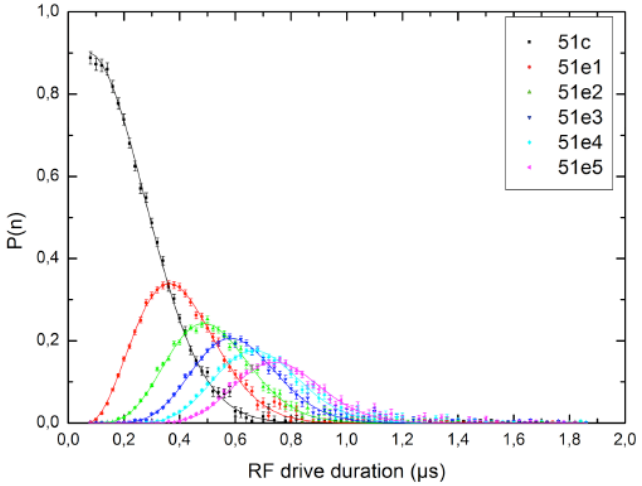




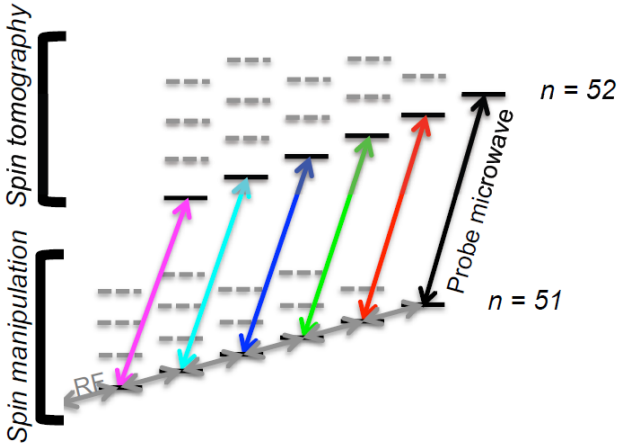


In the limit of low excitation ➡ Harmonic oscillator

Selective microwave addressing



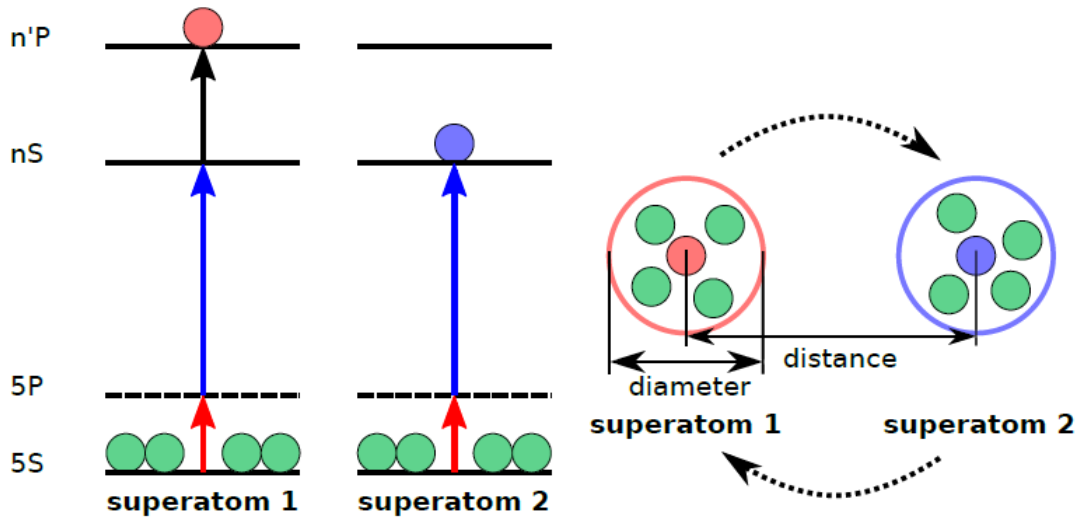
« Injection » of coherent state



All the tools of CQED

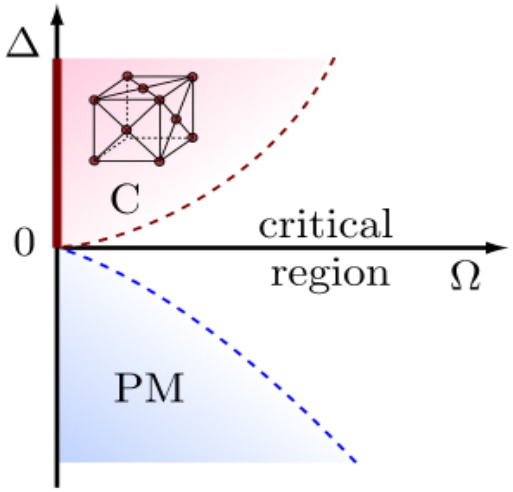
- ➡ Quantum simulator of a cavity
- ➡ Quantum Zeno dynamics
- ➡ Quantum control

Superatom hopping between 2 (and up to 10) sites



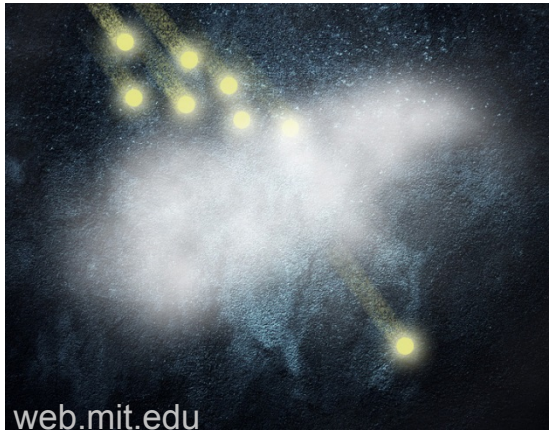
- Spatially resolved Rydberg excitation and detection
- Two-color excitation of S and P states
- Study of N = 2,3, … 10 atom Rydberg networks
- Focus on spatially resolved energy shifts (AC-Stark shifts)

Universität Heidelberg



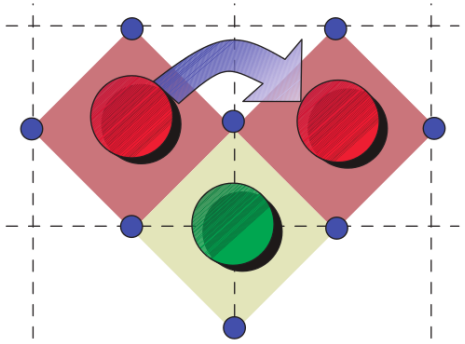
Quantum critical behaviour
Weimer *et al*, PRL 2008

Quantum nonlinear optics

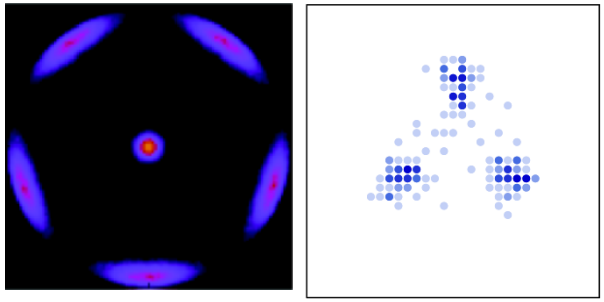


Dudin + Kuzmich, Science 2012
Peyronel et al., Nature 2012
Maxwell et al., PRL 2013

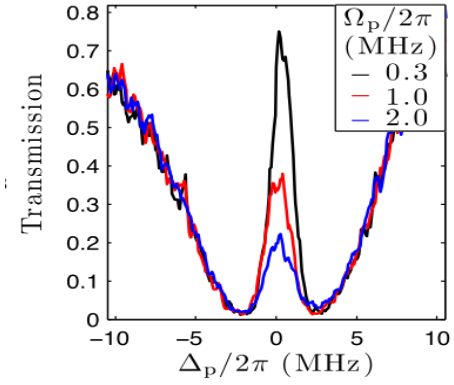
Quantum simulation



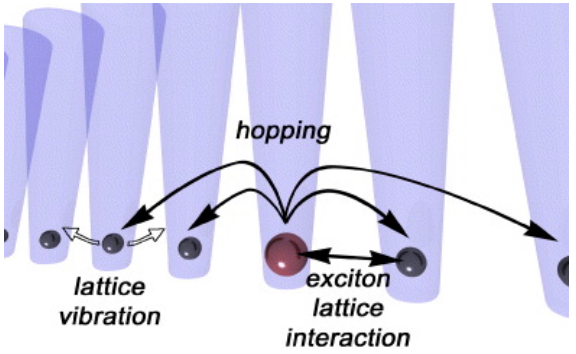
Weimer et al., Nature Phys. 201



Dynamical crystallisation
Pohl *et al*, PRL 2010
Schauß et al, Nature 2012



Rydberg EIT
Pritchard et al., PRL 2010

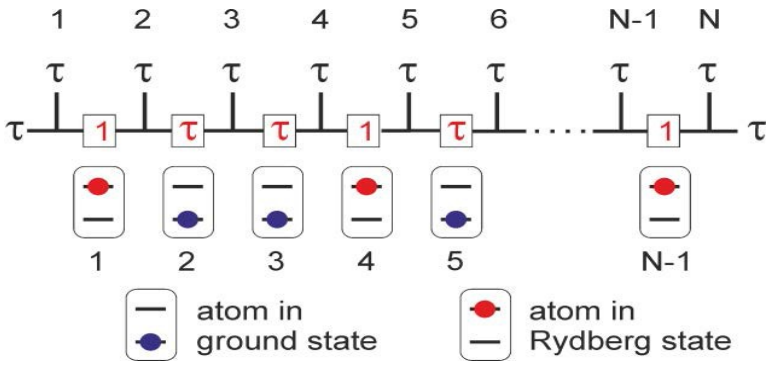


Electron-phonon interactions
Hague + MacCormick., NJP 201

Nottingham University

Strongly correlated spin systems

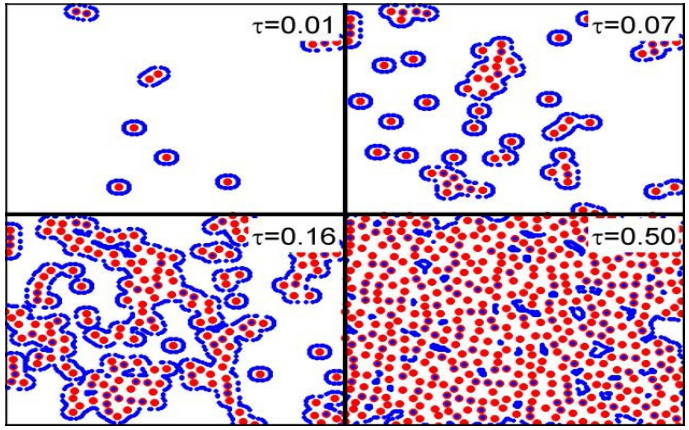
- Implementation of spin models with Rydberg and group II atoms
- analytic ground state solutions
- engineering of exotic Hamiltonians



PRL **106**, 025301 (2011); PRL **108**, 110603 (2012); PRL **108**, 110603 (2012); PRA **86**, 041601 (2012), PRL **110**, 143602 (2013)

Out-of-equilibrium phenomena

- Relaxation and thermalization
- Exploration of out-of-equilibrium soft-matter phenomena in Rydberg systems (glassiness, nucleation, aggregation, spontaneous ordering and self organization)



PRL **108**, 110603 (2012); PRL **109**, 020403 (2012); PRA **86**, 013408 (2012); J Stat Phys P02005 (2013); PRL **111**, 215305 (2013)

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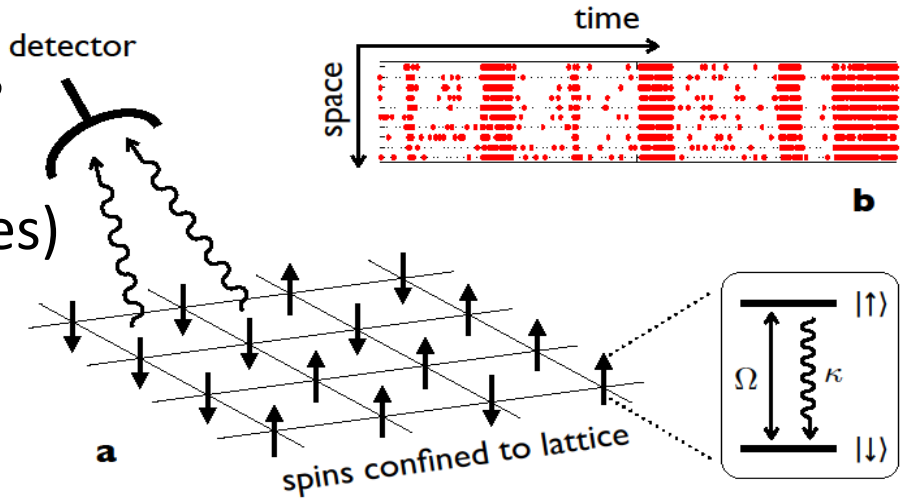
Dynamics of open quantum systems

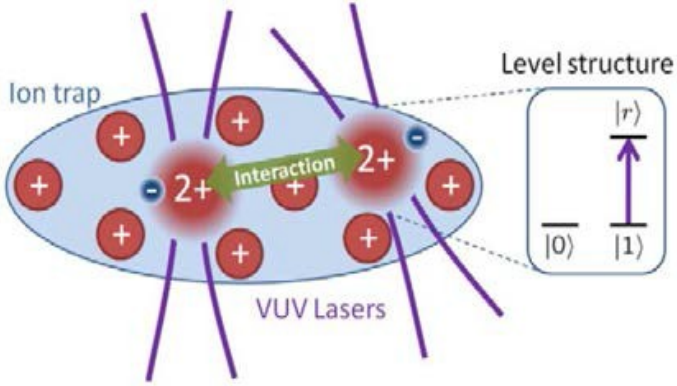
- Classification dynamical phases (Thermodynamics of QJ trajectories)
- Exotic dissipation mechanisms (long-ranged dissipation using Rydberg states)



PRL **104**, 160601 (2010); PRA **85**, 043620 (2012); PRL **109**, 233003 (2012); PRL **110**, 150401 (2013); PRL **112** (2014)

Rydberg ions

- Atomic physics
- Quantum information processing and simulation schemes

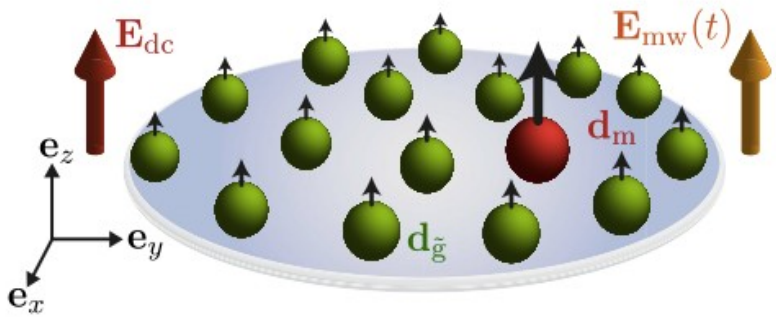


NJP **13**, 075014 (2011); PRL **108**, 110603 (2012);
PRA **87**, 052304 (2013); APB (2013)

Non-classical light sources

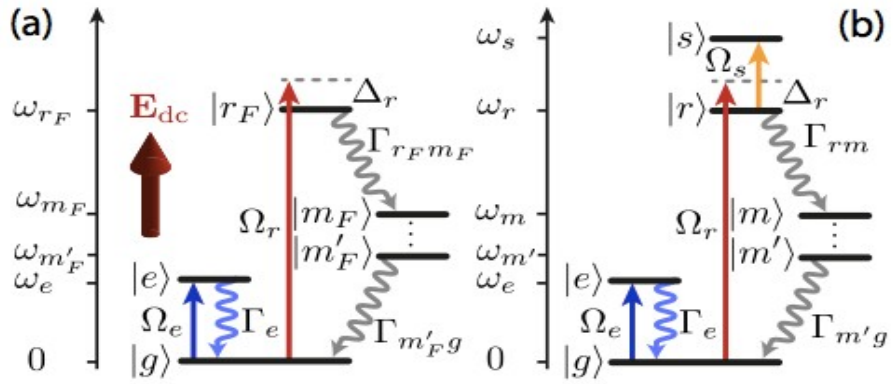
Hybrid systems

- **Rydberg atoms as reservoirs / resources:**
  - ✓ Cooling of (non bi-alkali) molecules
  - ✓ Interaction engineering in cold atomic / molecular gases (blue-shielding-ty



Rydberg-dressed atoms

Static electric field Microwave field

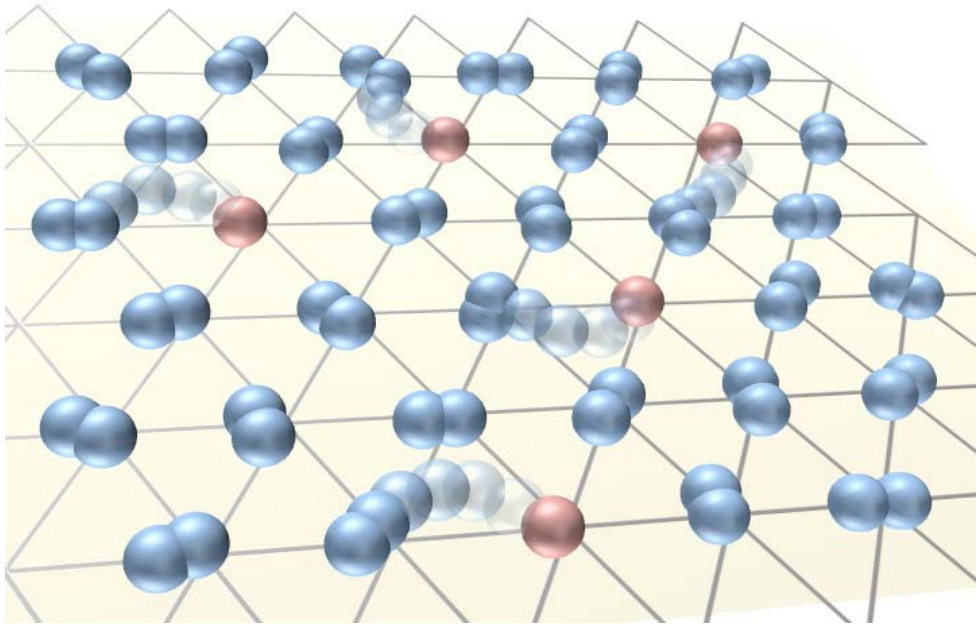


- **Long-range phonon dynamics in optomechanical arrays**
  - ✓Strong light-matter interactions with membrane stacks

with Xuereb, Genes, Paternostro, Dantan (see also Zoller et al. 2013)

Max Planck Institute - Dresden

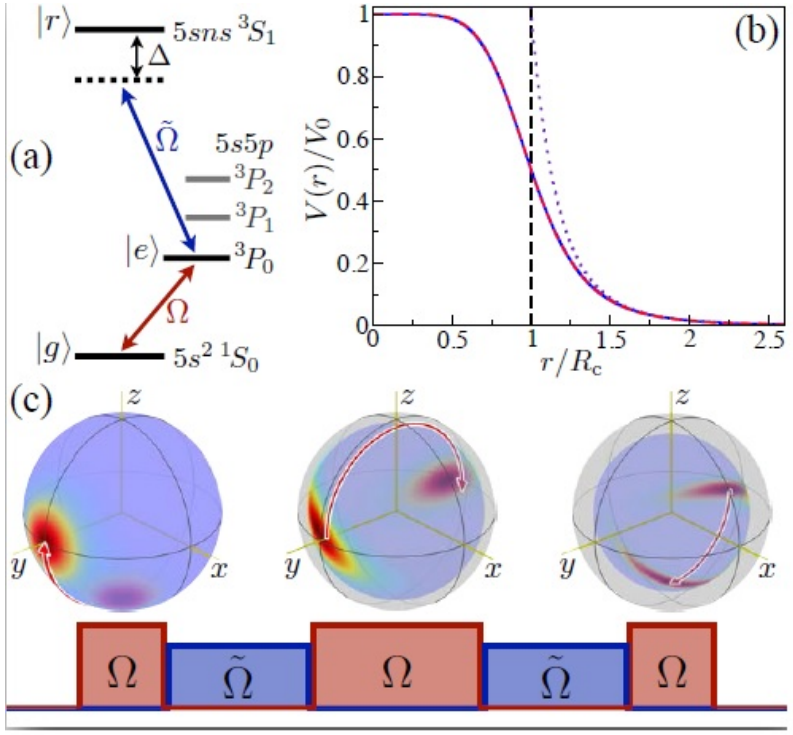
- **supersolidity from Rydberg-induced soft-core interactions**



T. Macrì, F. Maucher, F. Cinti & T. Pohl
Phys. Rev. A **87**, 061602(R) (2013)

F. Cinti, T. Macrì, W. Lechner, G. Pupillo & T. Pohl
Nature Comm. (to appear)

- **Rydberg-induced soft-core interactions in lattices**



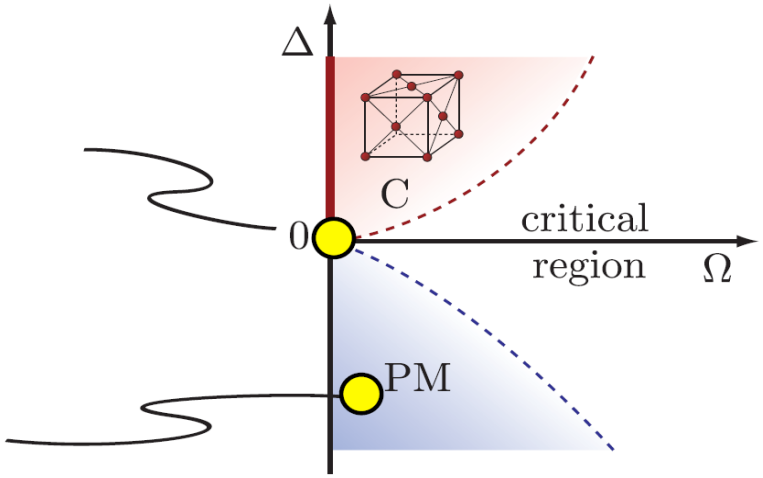
L.I.R. Gil, R. Mukherjee, E. Bridge,
M.P.A. Jones & T. Pohl, arXiv:1306.6240

T. Macrì & T. Pohl, arXiv:1308.5562

Universität Stuttgart (H.P. Büchler)

Quantum phase transition from paramagnet to crystalline phase

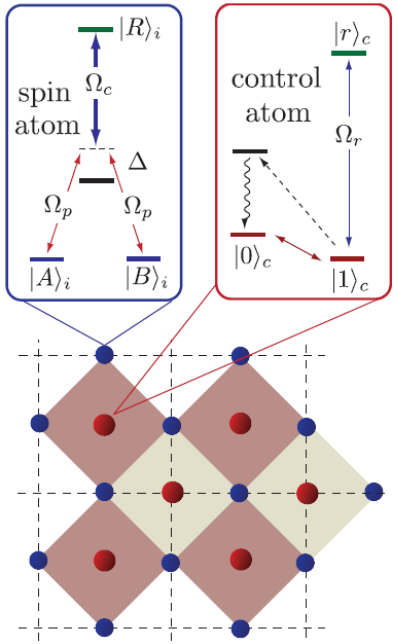
- novel universality class
- quantum critical behavior



Rydberg dressed interactions

- inducing an interaction for ground state atoms

- collective interaction due to large blockade radius



Rydberg quantum simulator

- digitial quantum simulation
- dissipative and coherent dynamics
- many-body interactions