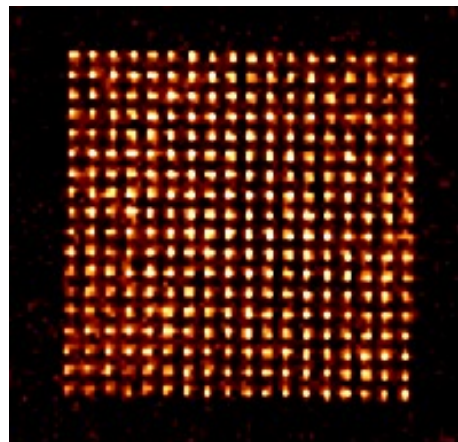


# *Quantum simulation with Rydberg atom arrays*

**Thierry Lahaye**

*Laboratoire Charles Fabry, CNRS & Institut d'Optique, Palaiseau, France*

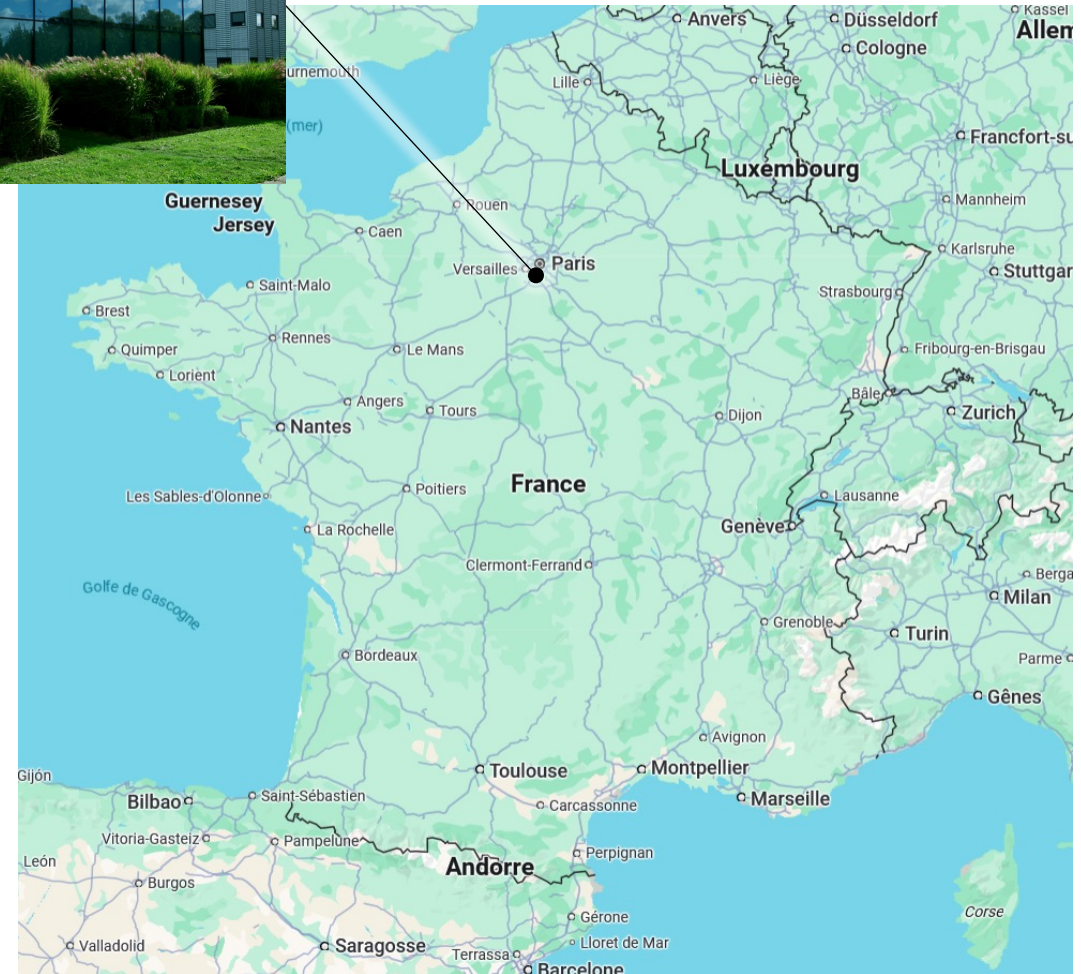


***ICTP-IBM School on Quantum Computing and Simulation***

ICTP, April 27, 2026

# Who am I?

- An experimentalist
- A CNRS researcher
- I work at *Institut d'Optique* in Palaiseau (~20 km south of Paris)



# Who am I?

- An experimentalist

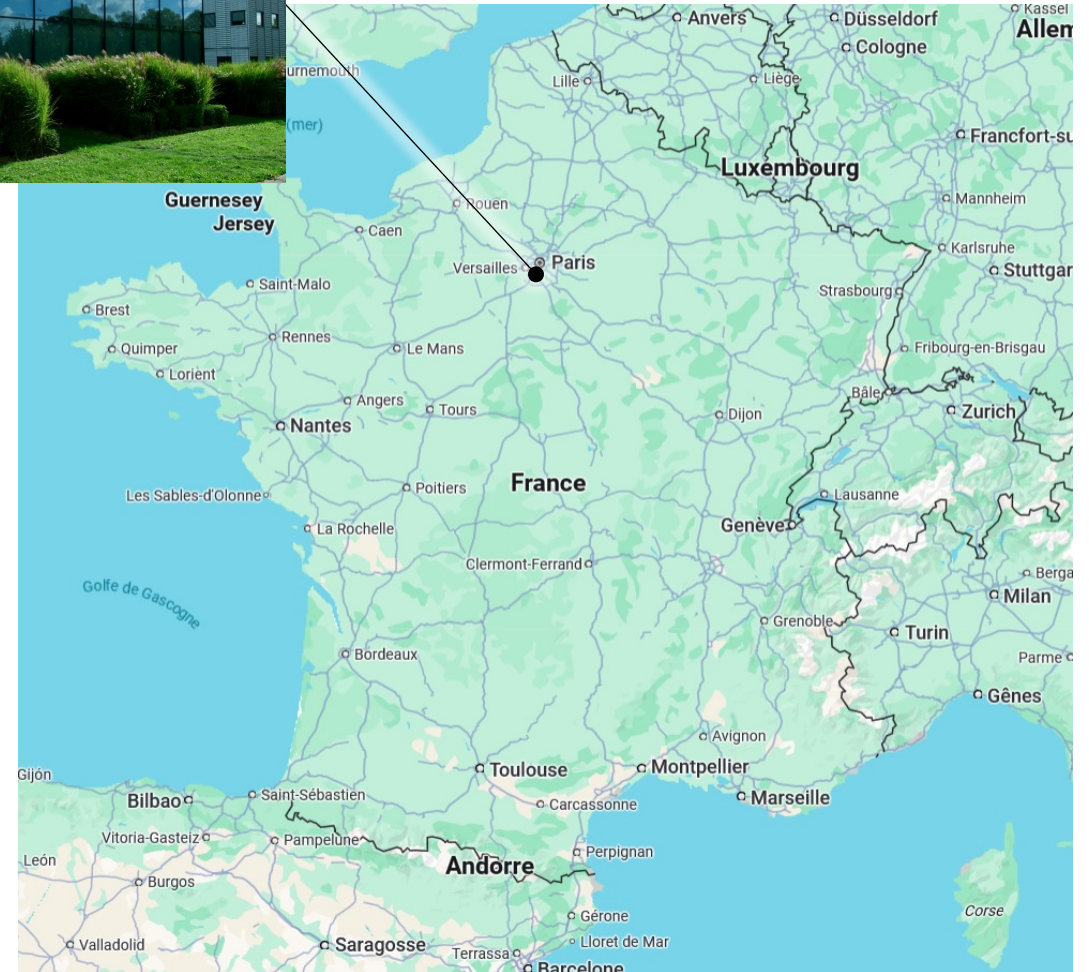
- A CNRS researcher



- I work at *Institut d'Optique* in Palaiseau (~20 km south of Paris)



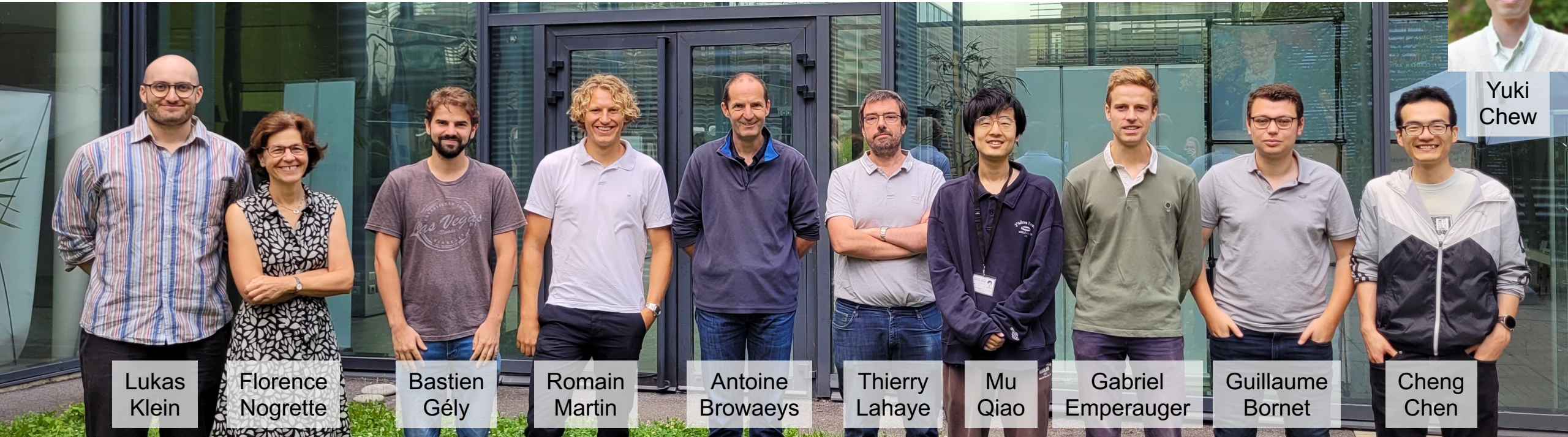
- I'm also a co-founder and scientific advisor at Pasqal



# The Rydberg team in Palaiseau



Yuki  
Chew



Lukas  
Klein

Florence  
Nogrette

Bastien  
Gély

Romain  
Martin

Antoine  
Browaey

Thierry  
Lahaye

Mu  
Qiao

Gabriel  
Emperauger

Guillaume  
Bornet

Cheng  
Chen

## Collaborators (theory):

A. Läuchli (EPFL), N. Yao (Harvard),  
T. Roscilde (ENS Lyon), H.P. Büchler (Stuttgart),  
A. Bohrdt & F. Grusdt (LMU), E. Demler (ETHZ)...

<https://atom-tweezers-io.org/>

Funding:



QUANTUM FLAGSHIP



## ***Before starting...***

- **Remain at very introductory level**

## ***Before starting...***

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- **Emphasis on experimental aspects**

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## ***Before starting...***

- **Remain at very introductory level**
- **Emphasis on experimental aspects**
- **Mix of slides and blackboard**
- **A few refs, but no attempt at being exhaustive**
- **Do not hesitate to ask questions during the lecture!**

# ***Before starting...***

- **Poll:**

Who is an experimentalist? Who is a theorist?

# *Before starting...*

- **Poll:**

Who is an experimentalist? Who is a theorist?

Who works with Rydberg atoms?

# ***Tentative outline***

- 1. General introduction & arrays of tweezers**
- 2. Rydberg atoms and their interactions**
- 3. Quantum simulation of spin models with arrays of Rydberg atoms**

# ***Section 1***

***1. Intro: quantum simulation of spin models***

***2. Single atoms in optical tweezers***

***3. Defect-free arrays***

***4. A few recent developments***

# Section 1

**1. Intro: quantum simulation of spin models**

2. Single atoms in optical tweezers

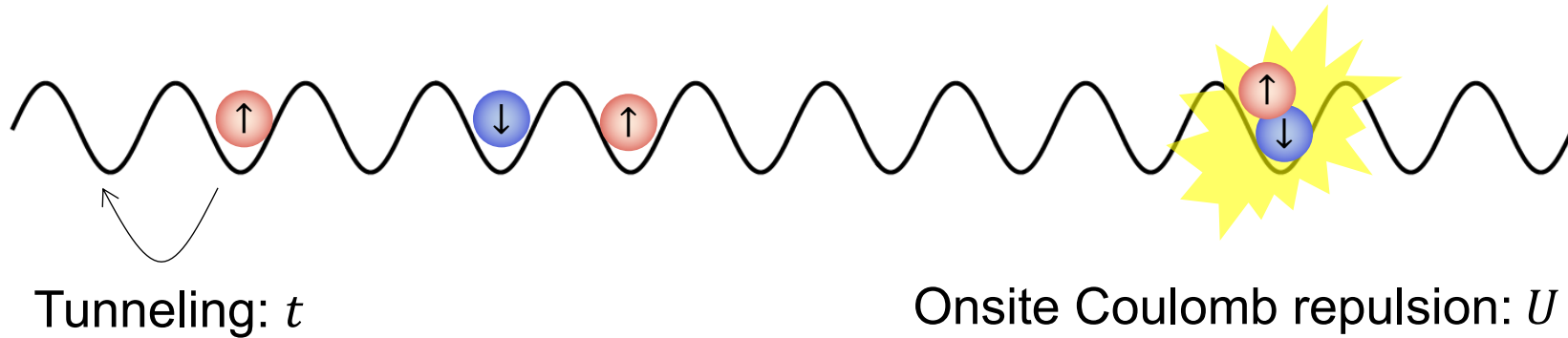
3. Defect-free arrays

4. A few recent developments

# ***Even simplistic models can't be solved...***

***Minimalistic model of interacting electrons in a crystal: Hubbard Hamiltonian (1963)***

$$H = -t \sum_{\langle i,j \rangle, \sigma} \left( c_{i,\sigma}^\dagger c_{j,\sigma} + \text{h.c.} \right) + U \sum_i n_{i,\uparrow} n_{i,\downarrow}$$



***No exact solution known in general... Maybe in some limits?***

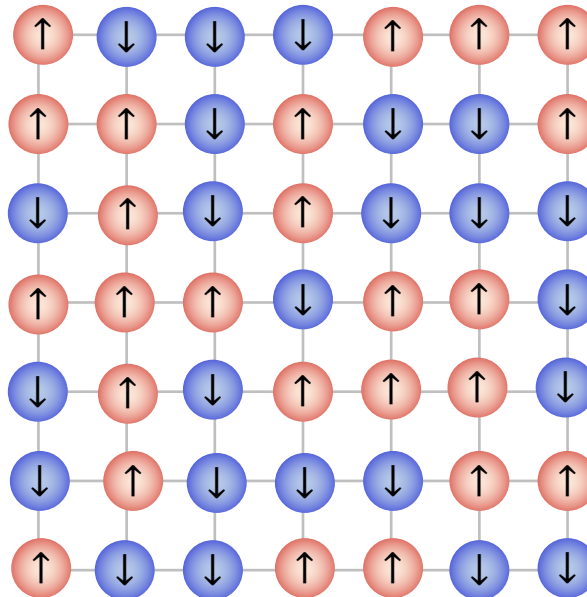
# Quantum magnetism

*Let's simplify further the "simplistic" model!*

Half filling  $N_{\uparrow} = N_{\downarrow}$

Limit  $t \ll U$ : no doubly-occupied sites

***Mott insulator phase***

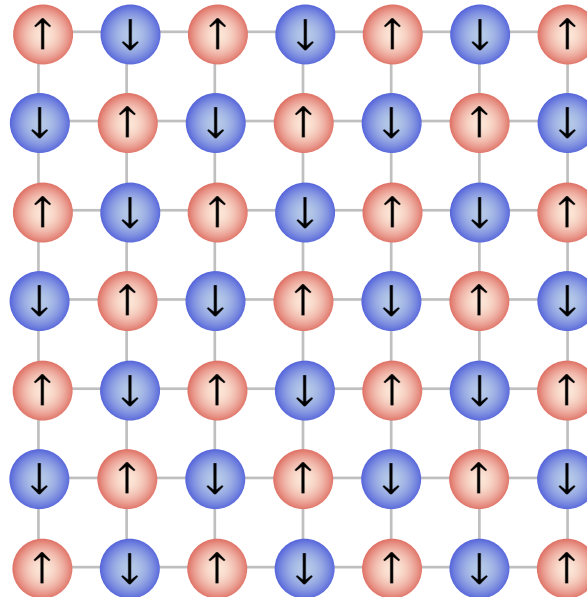


***Is it the end of the story?***

# Quantum magnetism

## *Not quite! Antiferromagnetic ordering*

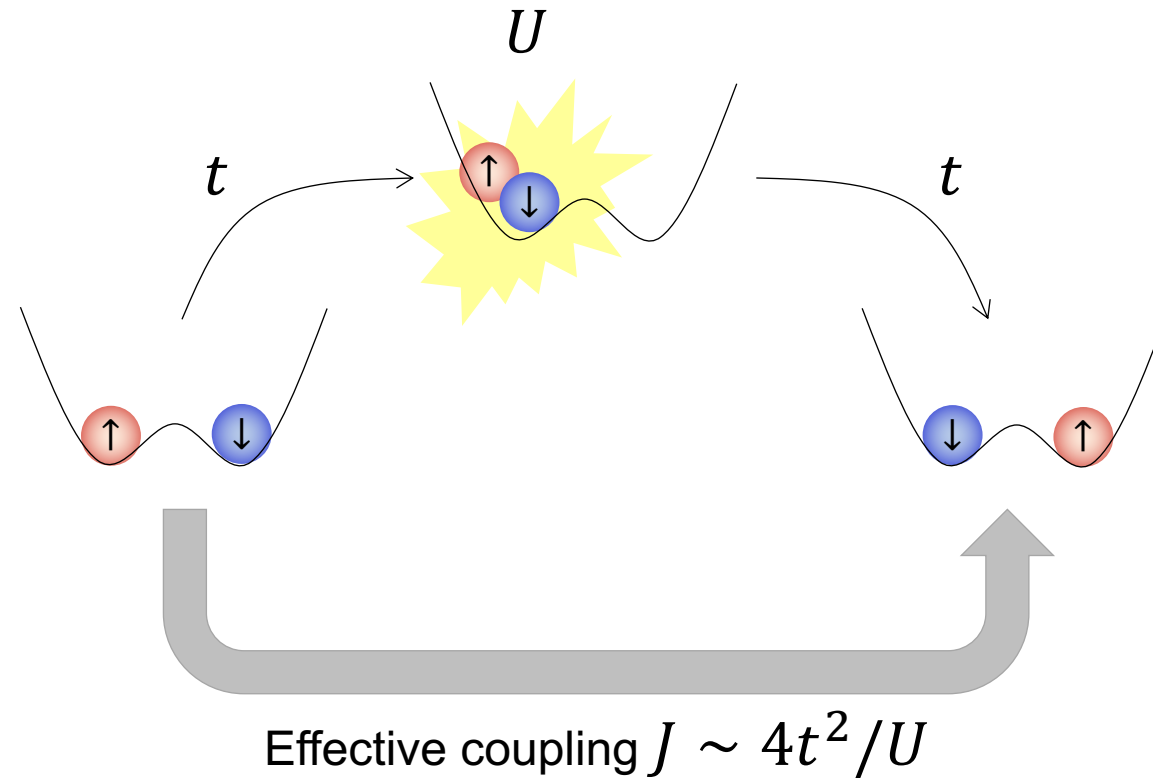
The system can lower its energy by ordering the spins



# Quantum magnetism

The system can lower its energy by ordering the spins

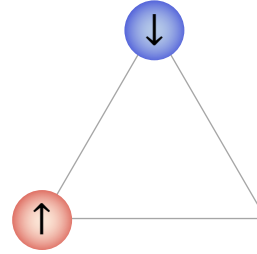
“Virtual” tunneling couples the states  $|\uparrow\downarrow\rangle$  et  $|\downarrow\uparrow\rangle$ , which lowers the energy



$$\text{Heisenberg Hamiltonian } H = J \sum_{\langle i,j \rangle} \vec{\sigma}_i \cdot \vec{\sigma}_j$$

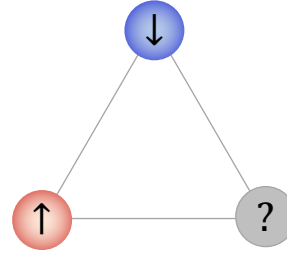
# *Still many open questions in quantum magnetism*

Geometric frustration, e.g., AF + triangular lattice:



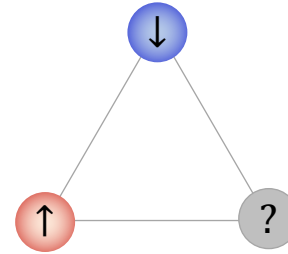
# *Still many open questions in quantum magnetism*

Geometric frustration, e.g., AF + triangular lattice:



# Still many open questions in quantum magnetism

Geometric frustration, e.g., AF + triangular lattice:

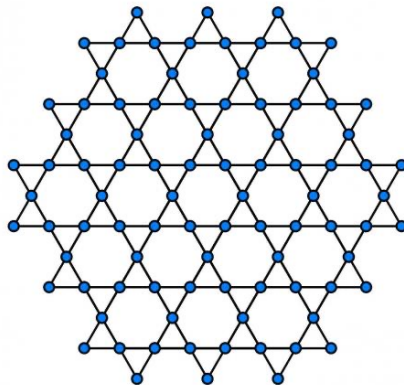


Heisenberg

$$H = J \sum_{\langle i,j \rangle} \vec{\sigma}_i \cdot \vec{\sigma}_j$$

+

Kagome lattice



“Spin liquids”

- No magnetic order down to  $T = 0$
- Massive entanglement
- Exotic, non-local elementary excitations (*anyons*)



# A zoo of spin Hamiltonians

Heisenberg  $H = J \sum_{\langle i,j \rangle} \vec{\sigma}_i \cdot \vec{\sigma}_j$   $\vec{\sigma} = (\sigma_x, \sigma_y, \sigma_z)$ : Pauli matrices

Ising model  $H_{\text{Ising}} = \sum_{i,j} J_{ij} \sigma_z^i \sigma_z^j$

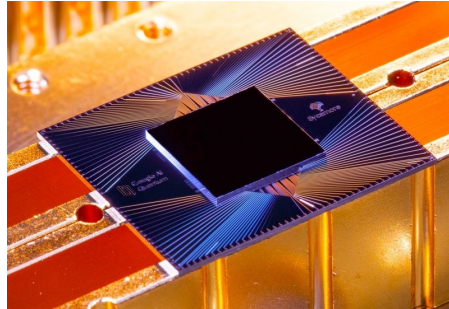
XY model  $H_{XY} = \sum_{i,j} J_{ij} (\sigma_x^i \sigma_x^j + \sigma_y^i \sigma_y^j)$

XXZ model  $H = \sum_{i,j} J_{ij} (\sigma_x^i \sigma_x^j + \sigma_y^i \sigma_y^j + \Delta \sigma_z^i \sigma_z^j)$

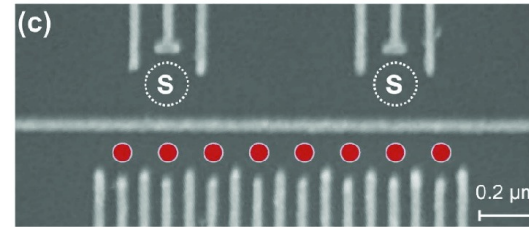
Each in many variants: Lattice geometry, range of couplings...

# Many platforms

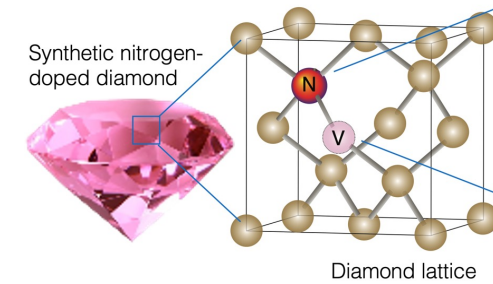
Superconducting qubits



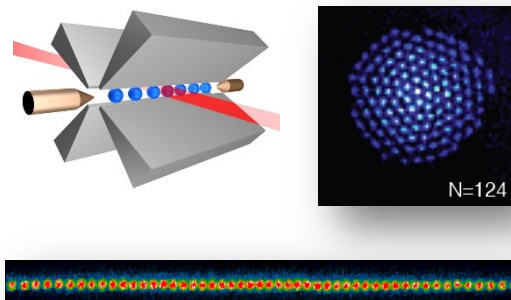
Electron quantum dots



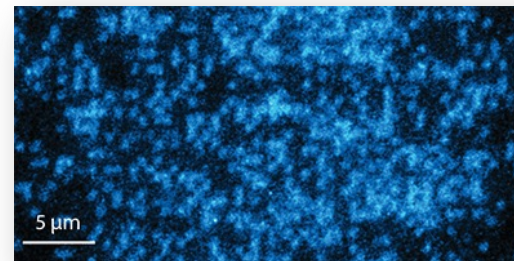
Defects in solids



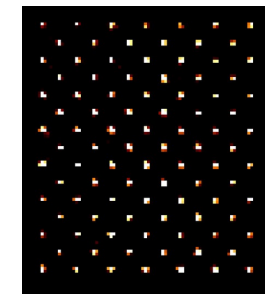
Trapped ions



Quantum gas microscopes

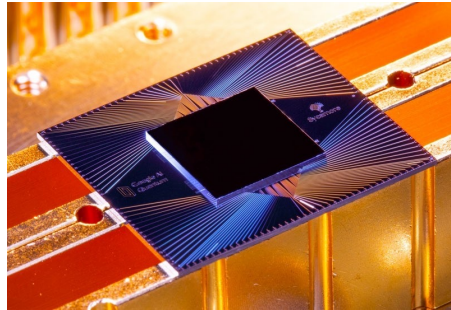


Rydberg tweezer arrays

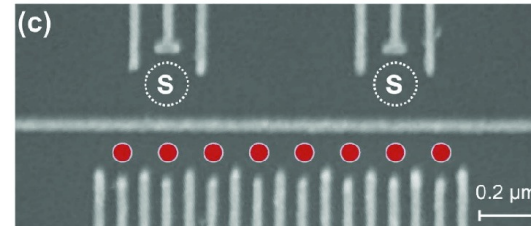


# Many platforms

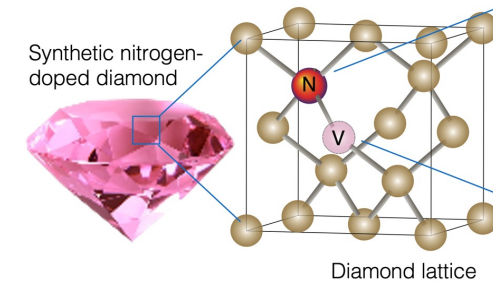
Superconducting qubits



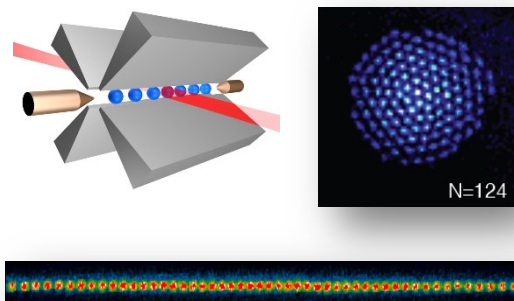
Electron quantum dots



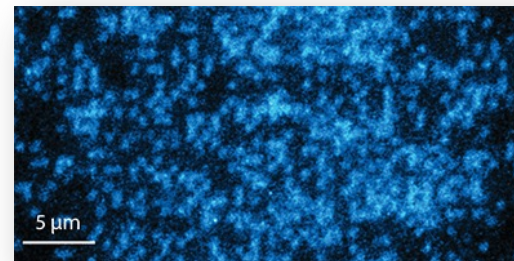
Defects in solids



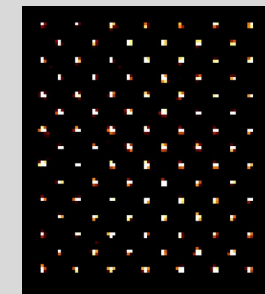
Trapped ions



Quantum gas microscopes



Rydberg tweezer arrays



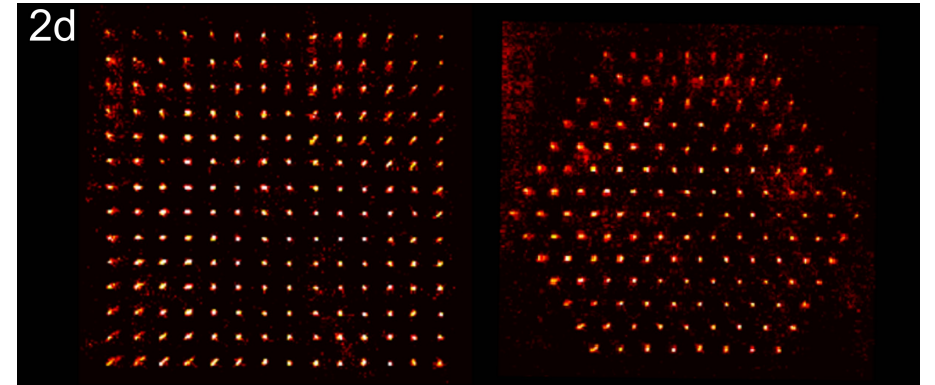
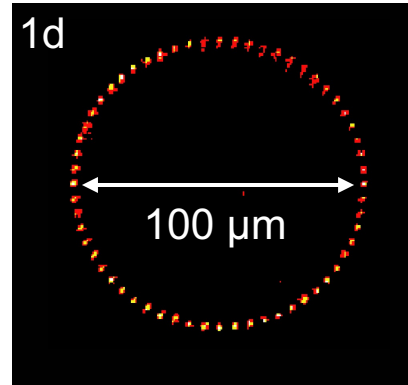
# Rydberg atom arrays

- **Arrays of single atoms**

Full control of geometry in 2D

Up to 500 atoms

Spacing: a few microns



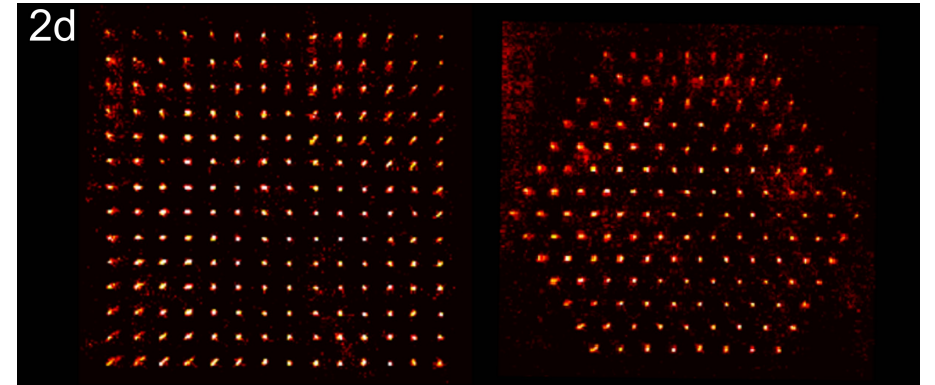
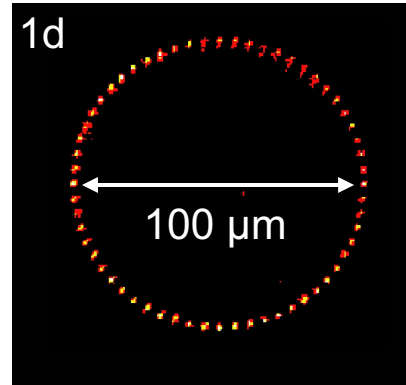
# Rydberg atom arrays

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Up to 500 atoms

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- **Strong interactions via Rydberg excitation**

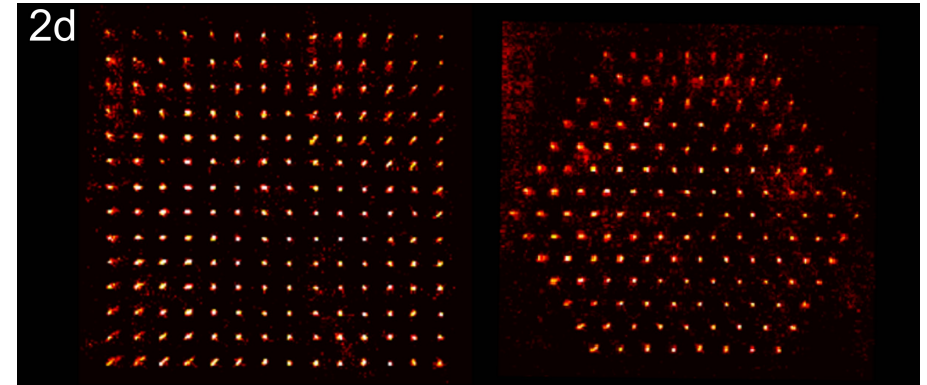
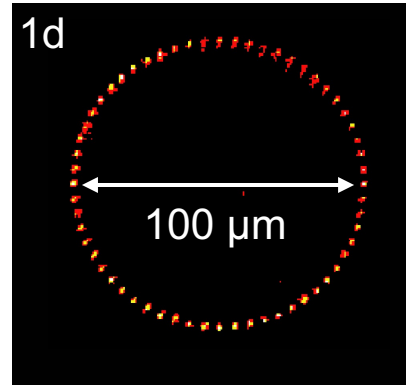
Interaction strength: 1 to 10 MHz for  $R \sim 5 \mu\text{m}$

Lifetime: 100 to 200  $\mu\text{s}$

# Rydberg atom arrays

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- **Strong interactions via Rydberg excitation**

Interaction strength: 1 to 10 MHz for  $R \sim 5 \mu\text{m}$   
Lifetime: 100 to 200  $\mu\text{s}$

- ***Implement quantum gates***

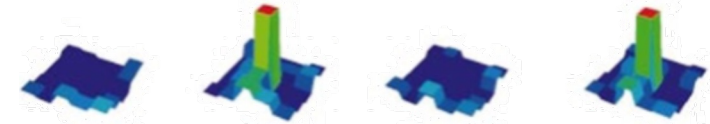
- ***Quantum simulation of spin models***

Ising (van der Waals interactions)

XY (resonant dipole-dipole interaction)

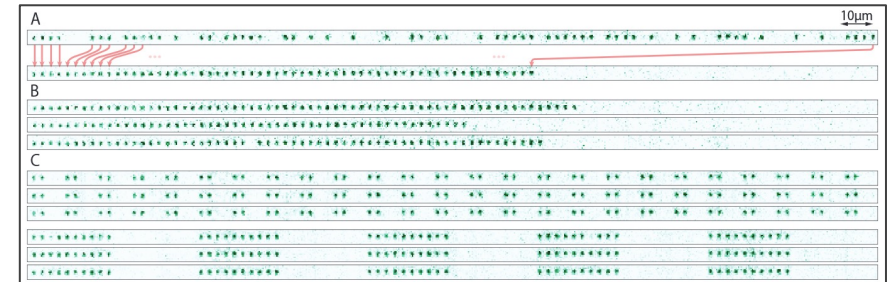
# Rydberg atoms and optical tweezers

**2001:** Single atoms in optical tweezers (Grangier)



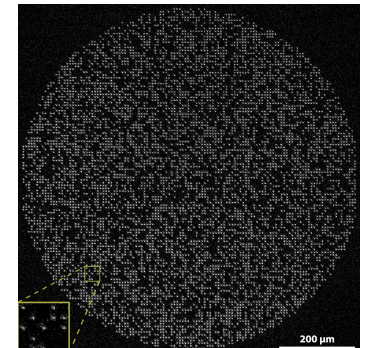
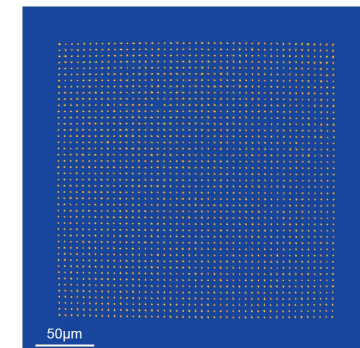
**2009:** Entanglement of 2 atoms with Rydberg blockade (Browaeys, Saffman)

**2016:** Rearrangement into defect-free arrays (Browaeys, Lukin)



**2021:** Quantum simulations of Ising model with 200+ atoms (Browaeys, Lukin)

**2024:** Logical qubits (Lukin)  
Large arrays > 2000 atoms (Endres, Pan)





# Section 1

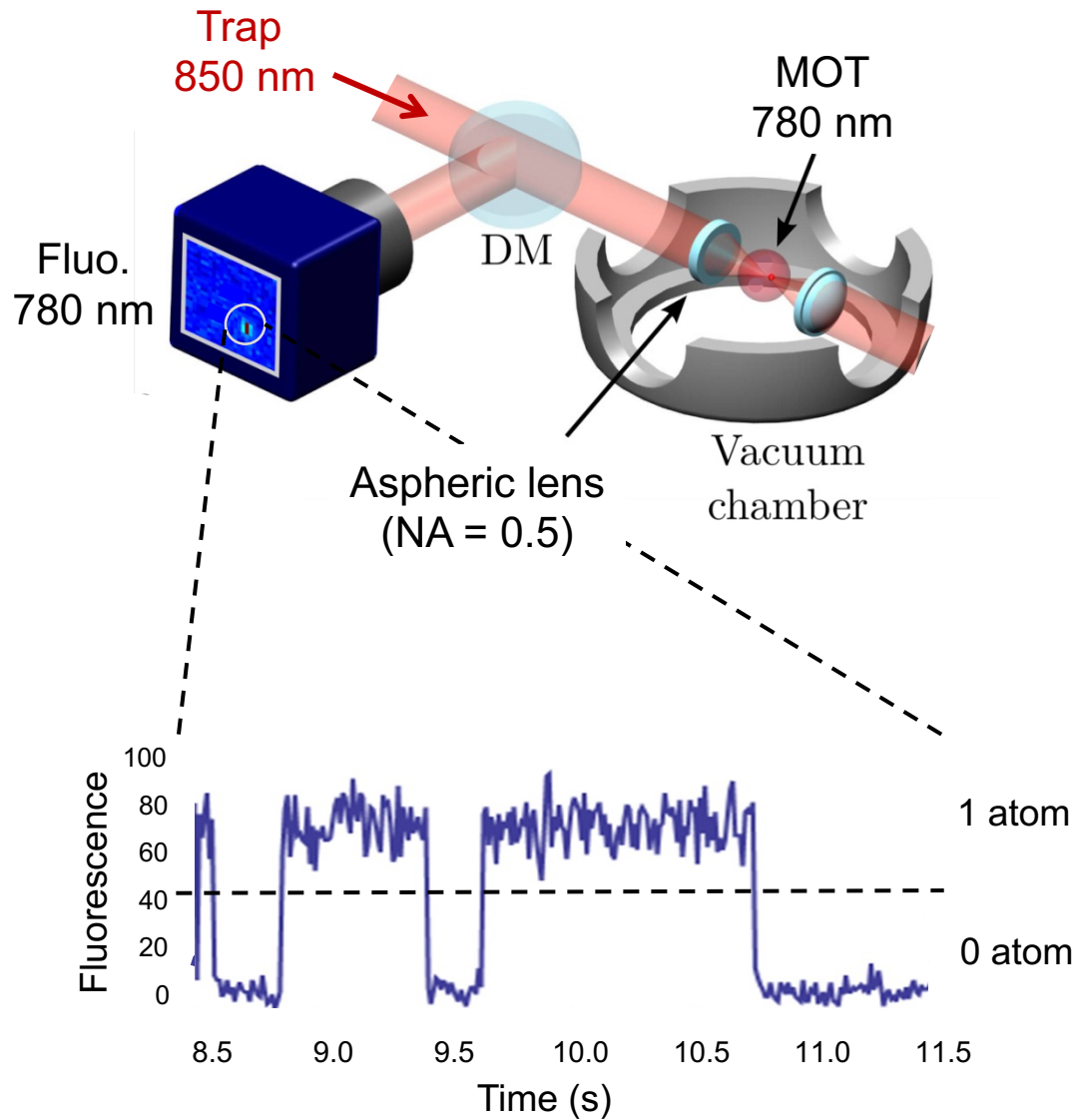
*1. Intro: quantum simulation of spin models*

**2. Single atoms in optical tweezers**

*3. Defect-free arrays*

*4. A few recent developments*

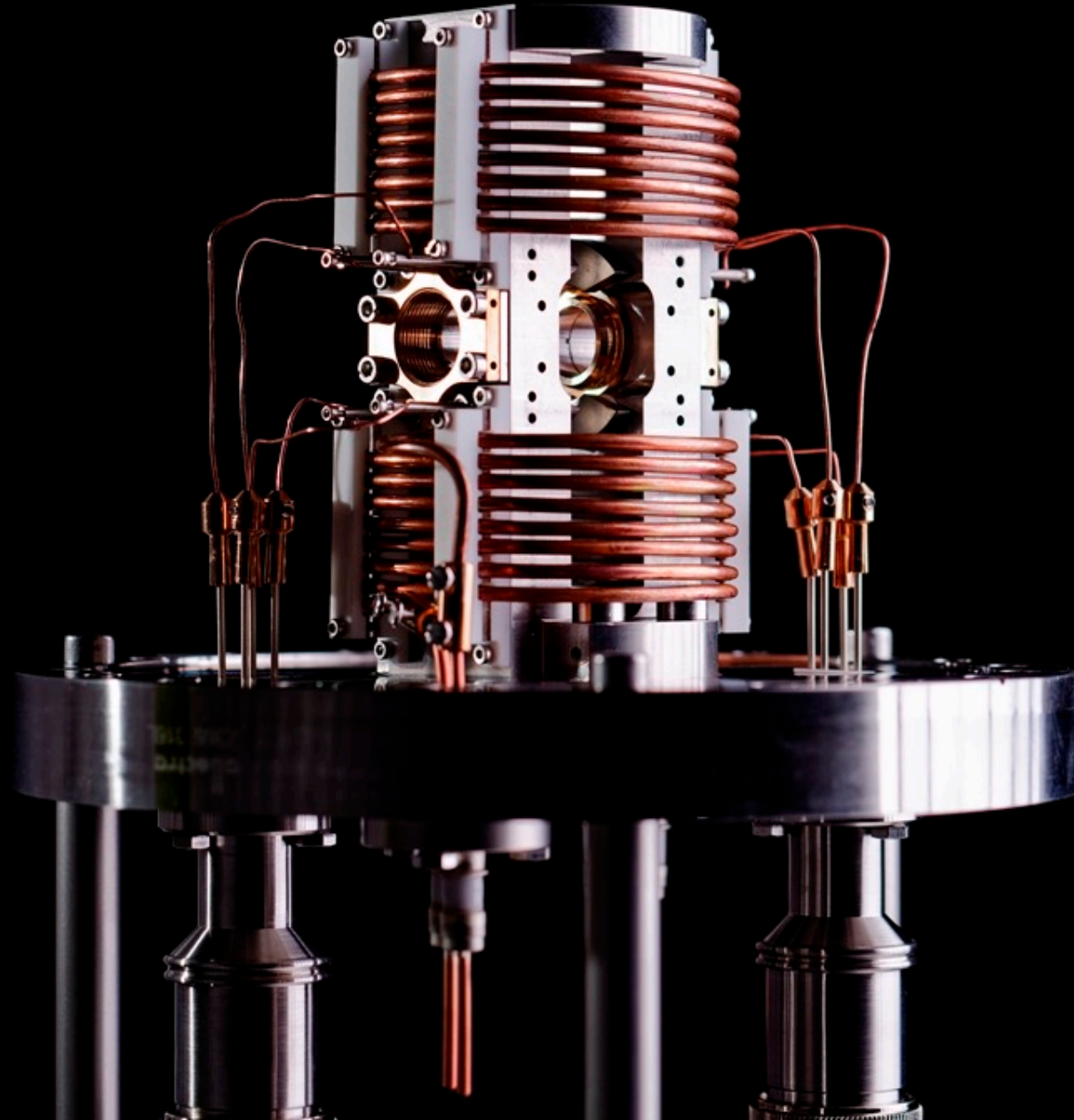
# Single atoms in optical tweezers



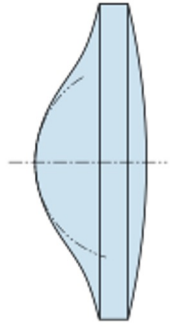
- 1  $\mu\text{m}$  waist optical tweezers loaded from MOT
- At most one atom due to light-assisted collisions
- 50-55% loading probability:

***Non-deterministic  
single-atom source!***

# *The CHADOQ experiment (2011-2025)*



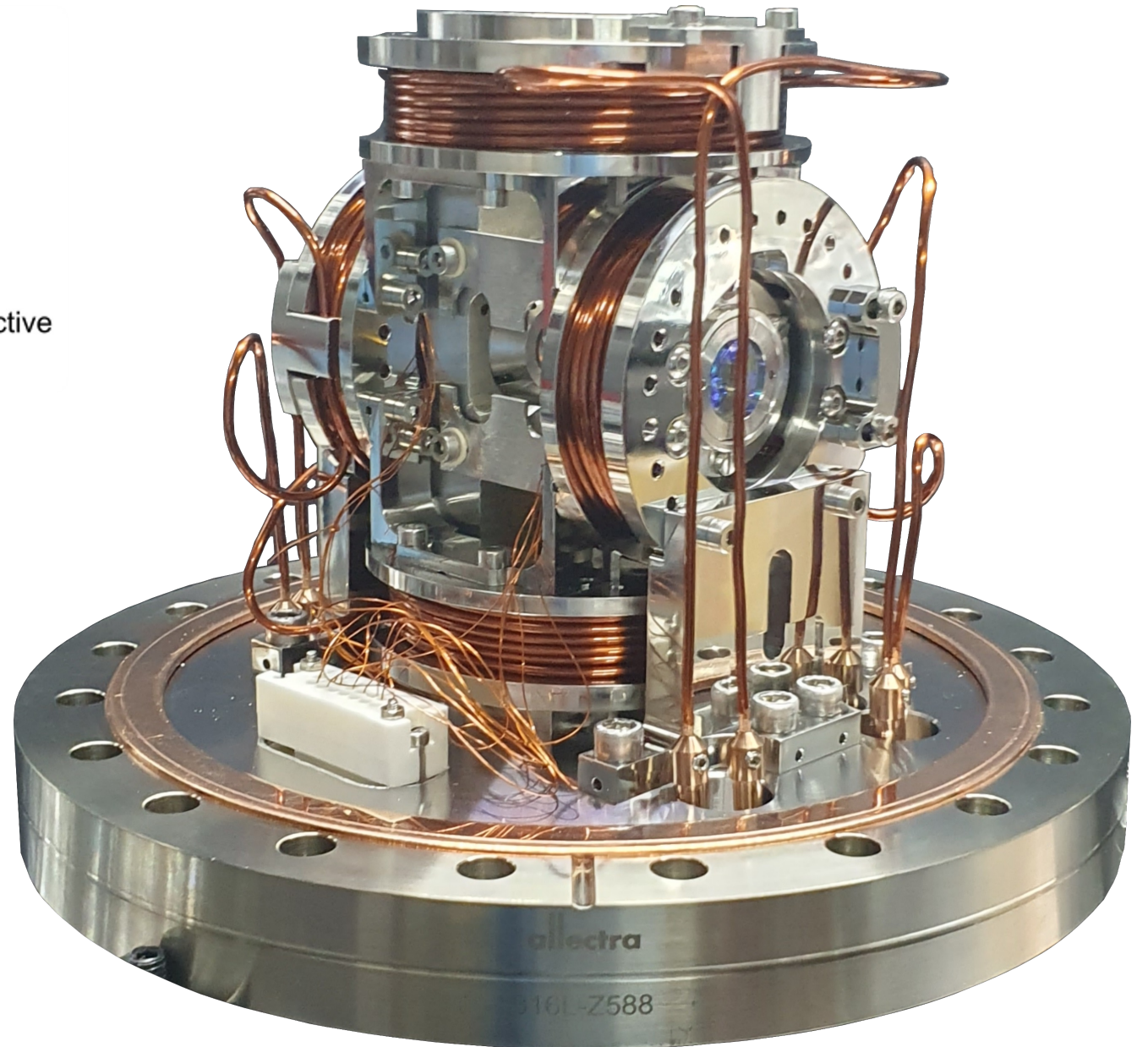
# *A new-generation setup*



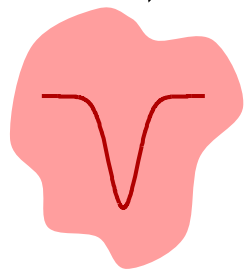
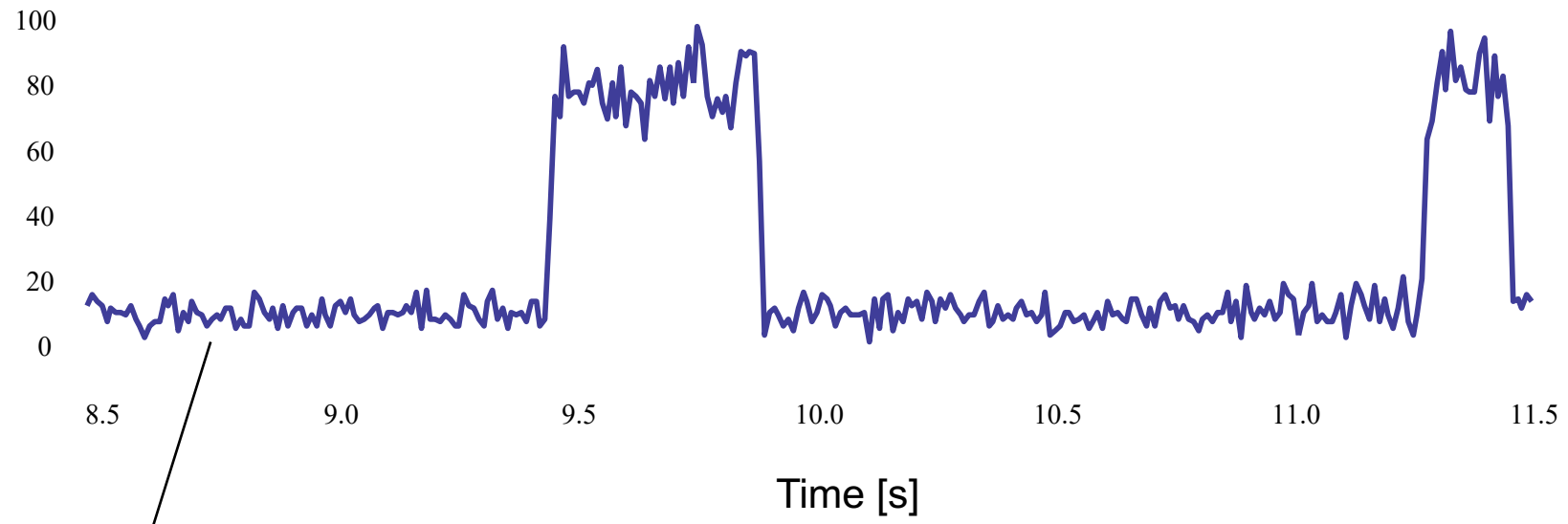
Aspheric lens



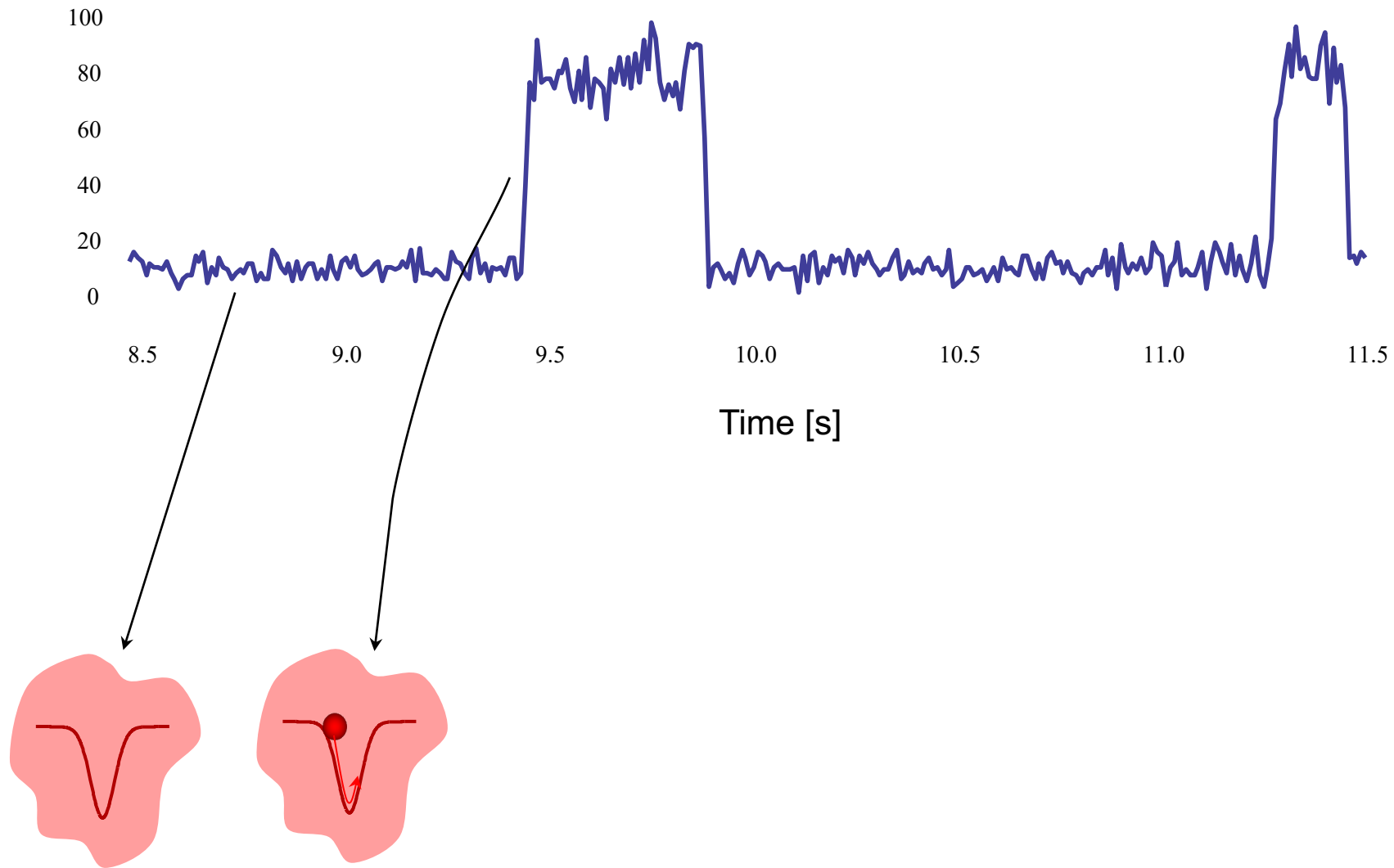
UHV compatible microscope objective  
(Special Optics)



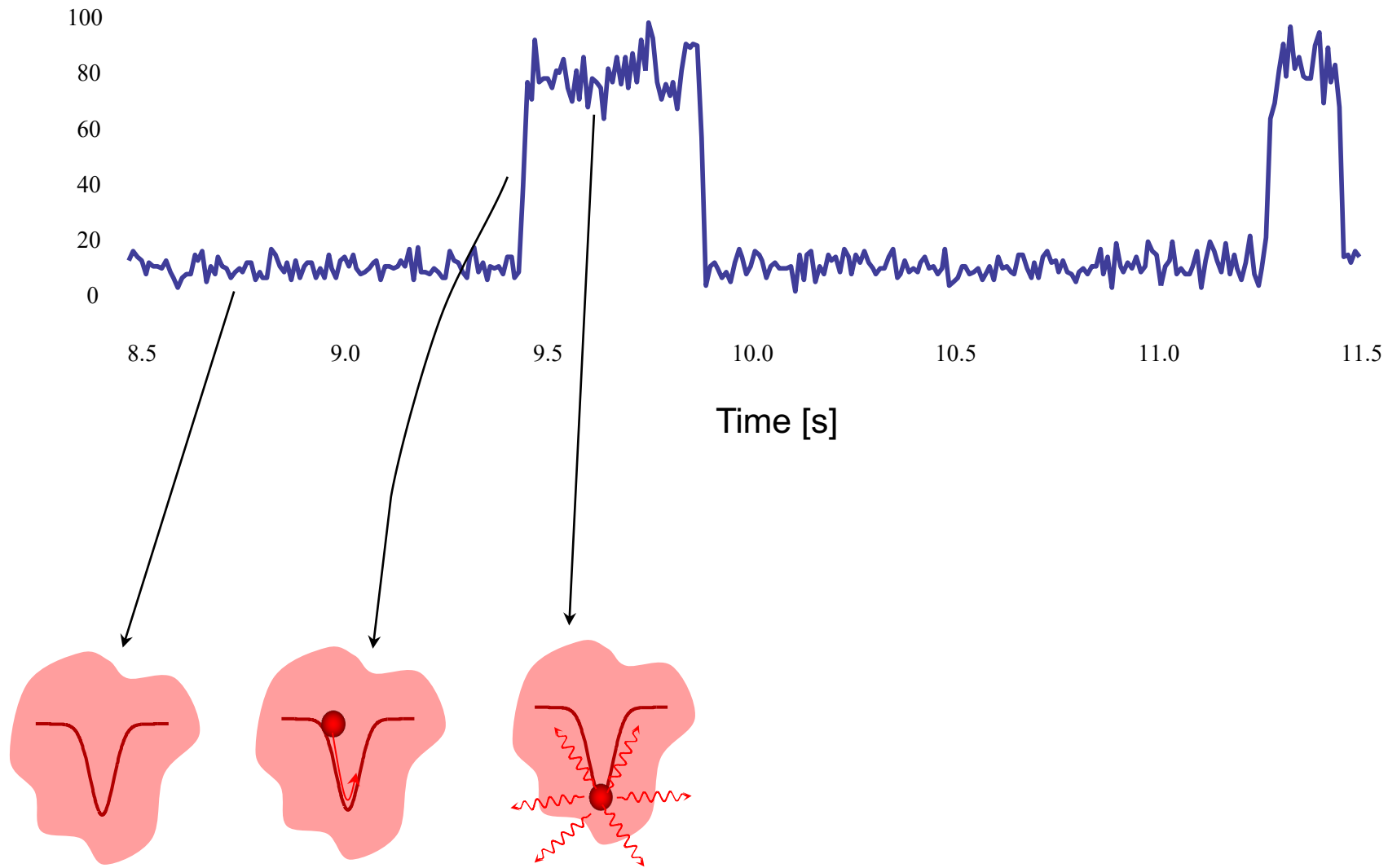
# *Why just zero or one atom?*



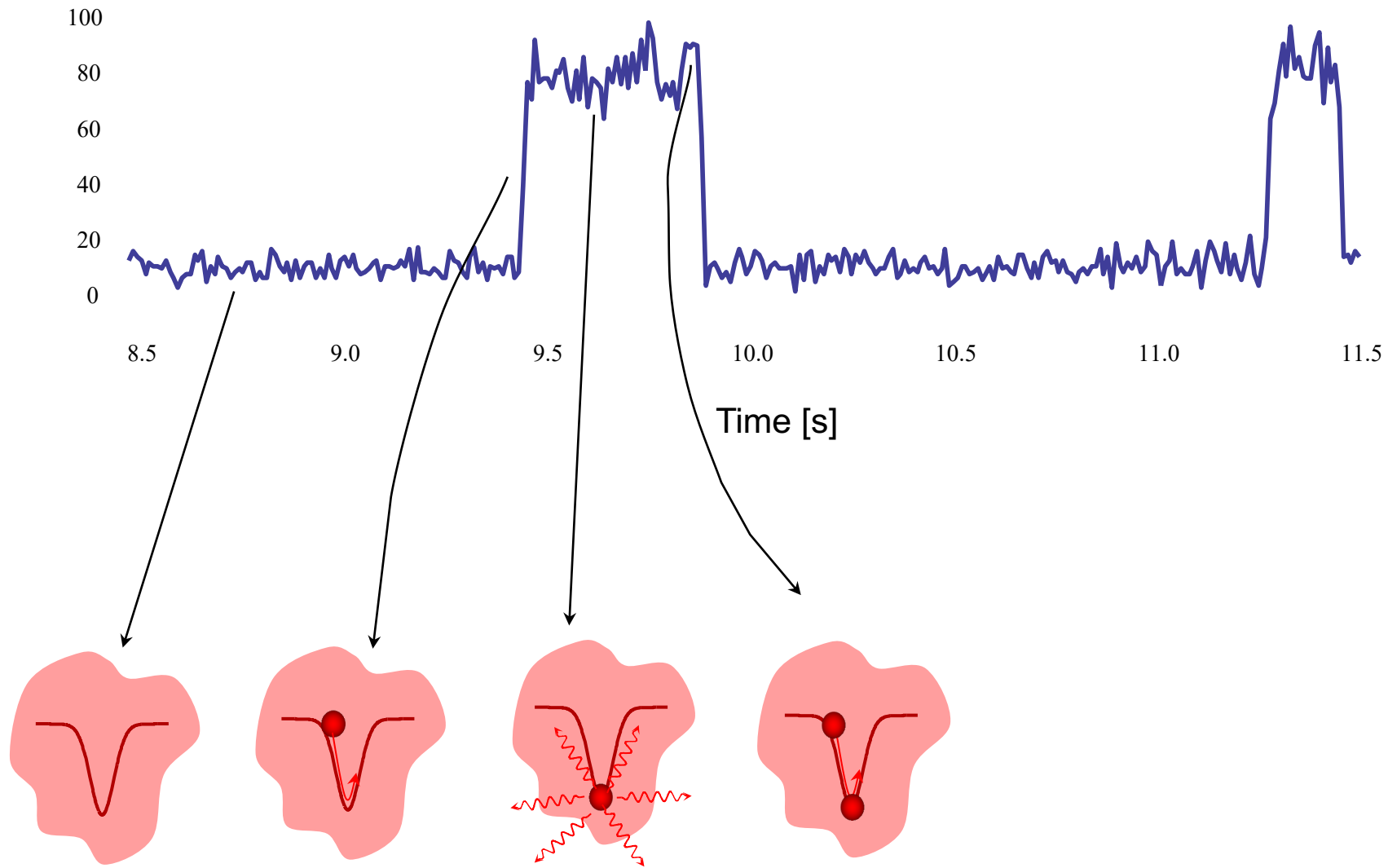
# Why just zero or one atom?



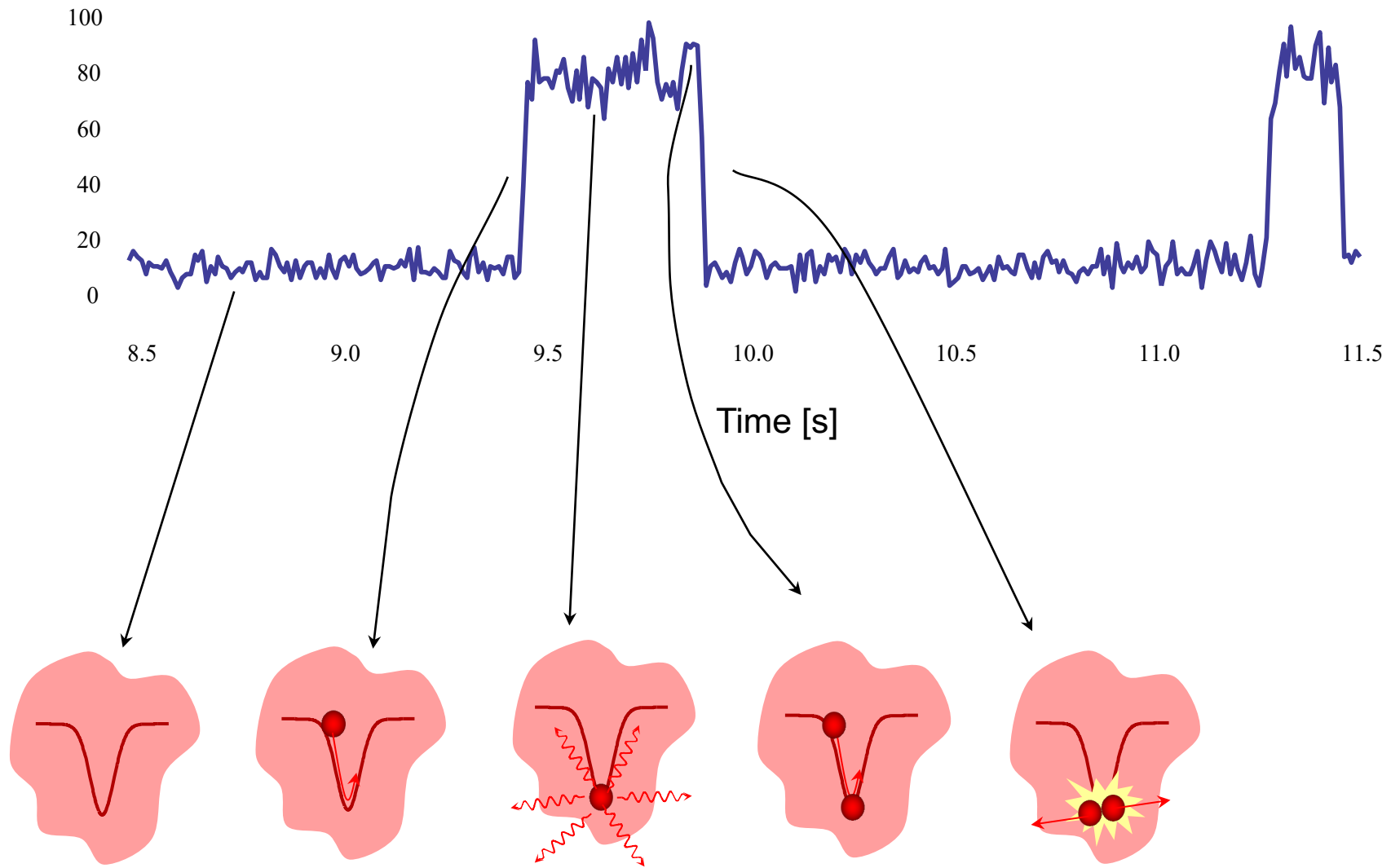
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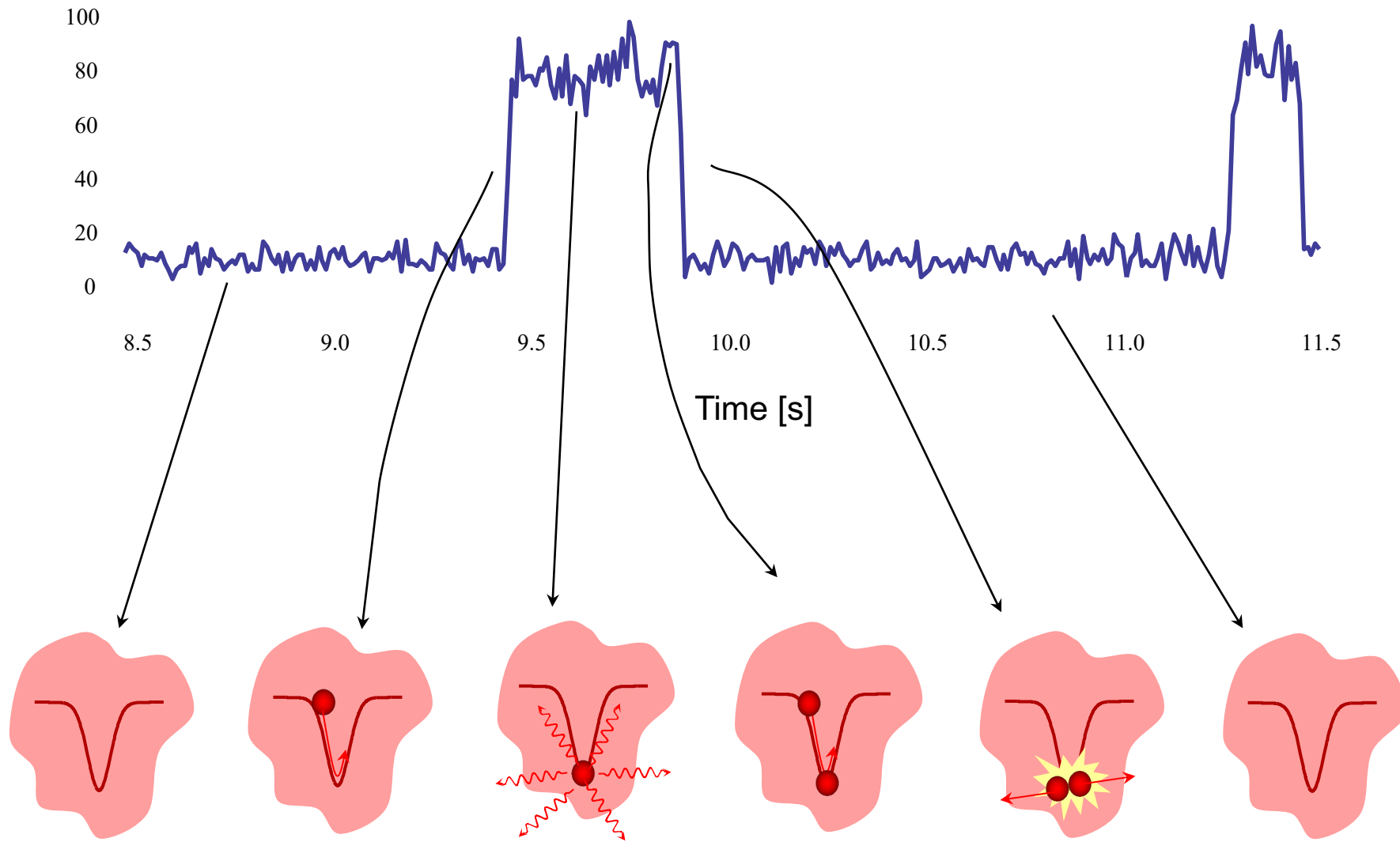
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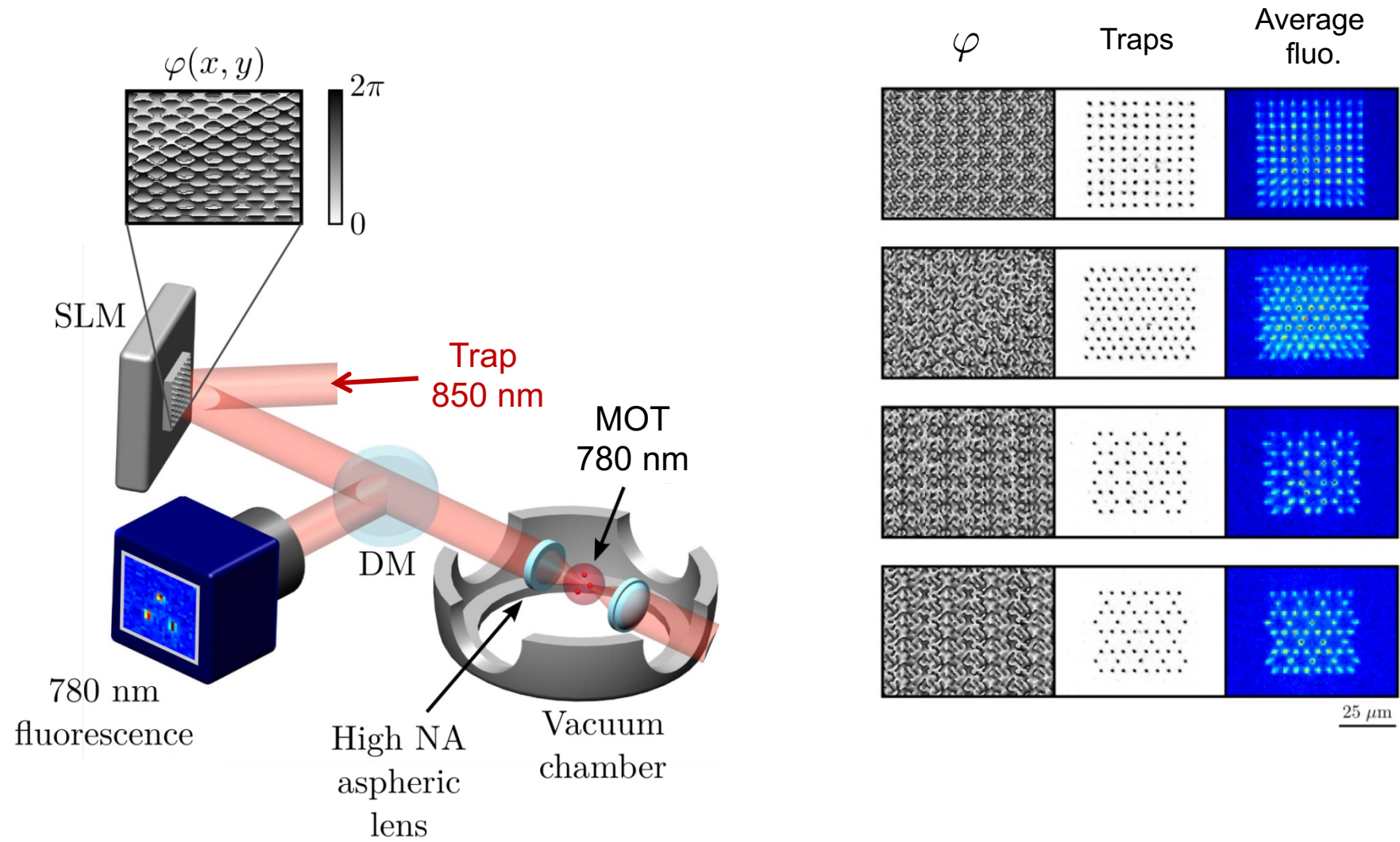
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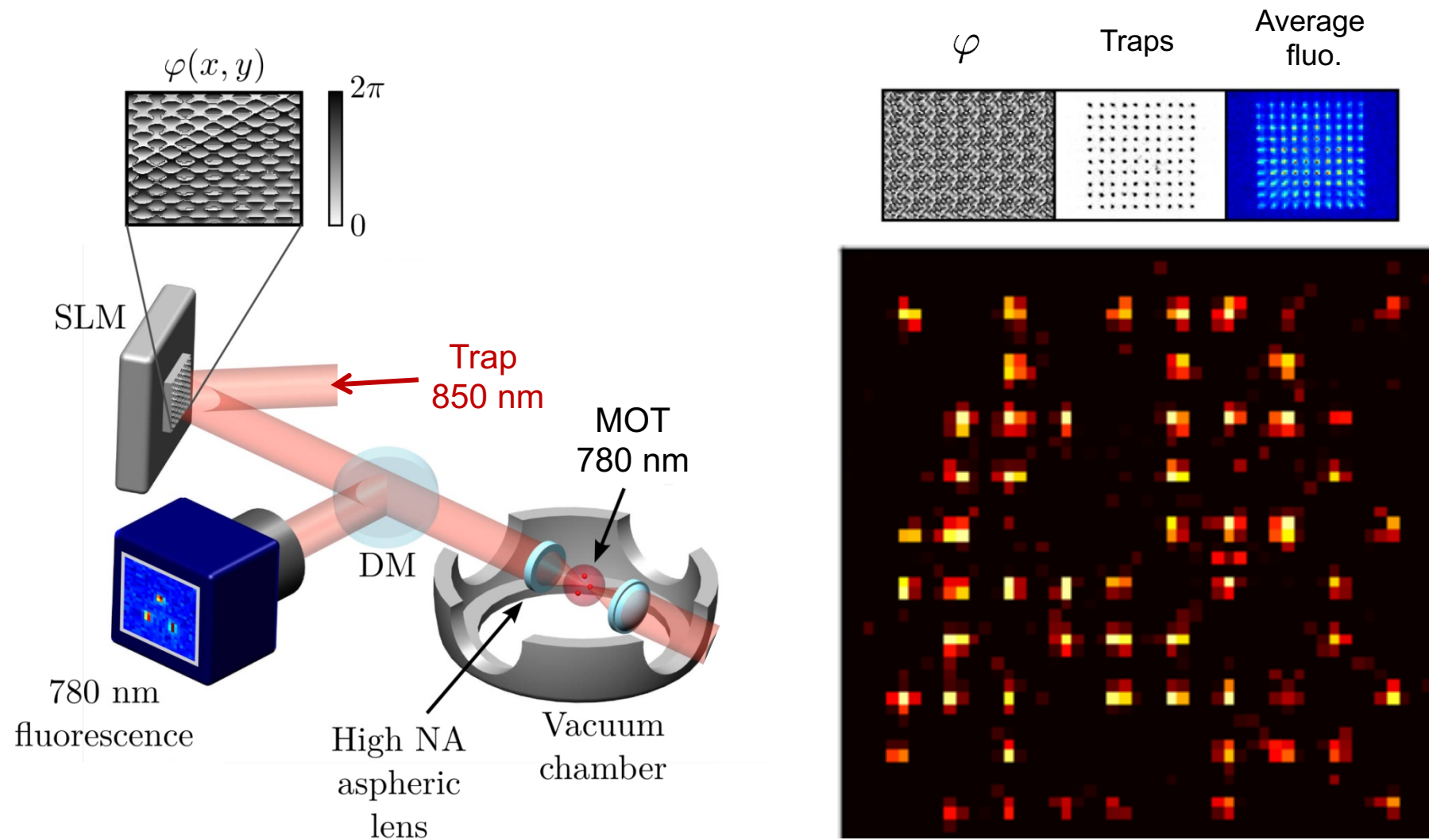
# Why just zero or one atom?



# Arrays of single atoms



# Arrays of single atoms



# Section 1

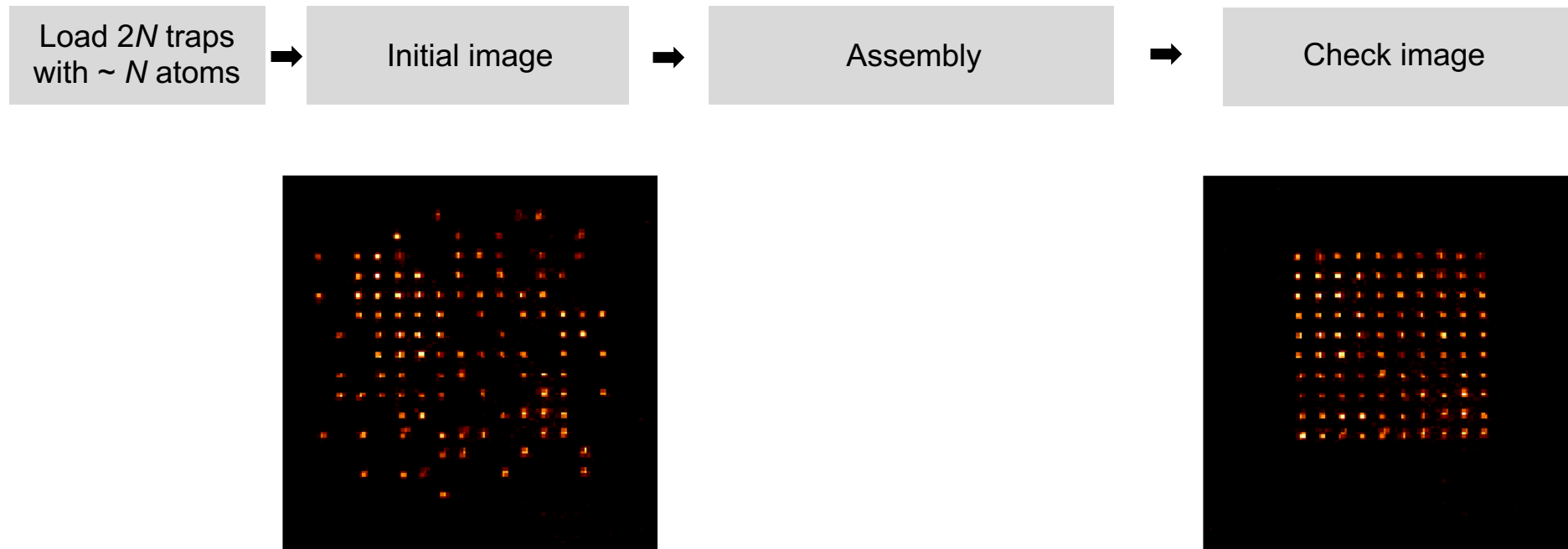
*1. Intro: quantum simulation of spin models*

*2. Single atoms in optical tweezers*

**3. Defect-free arrays**

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# Atom-by-atom assembly



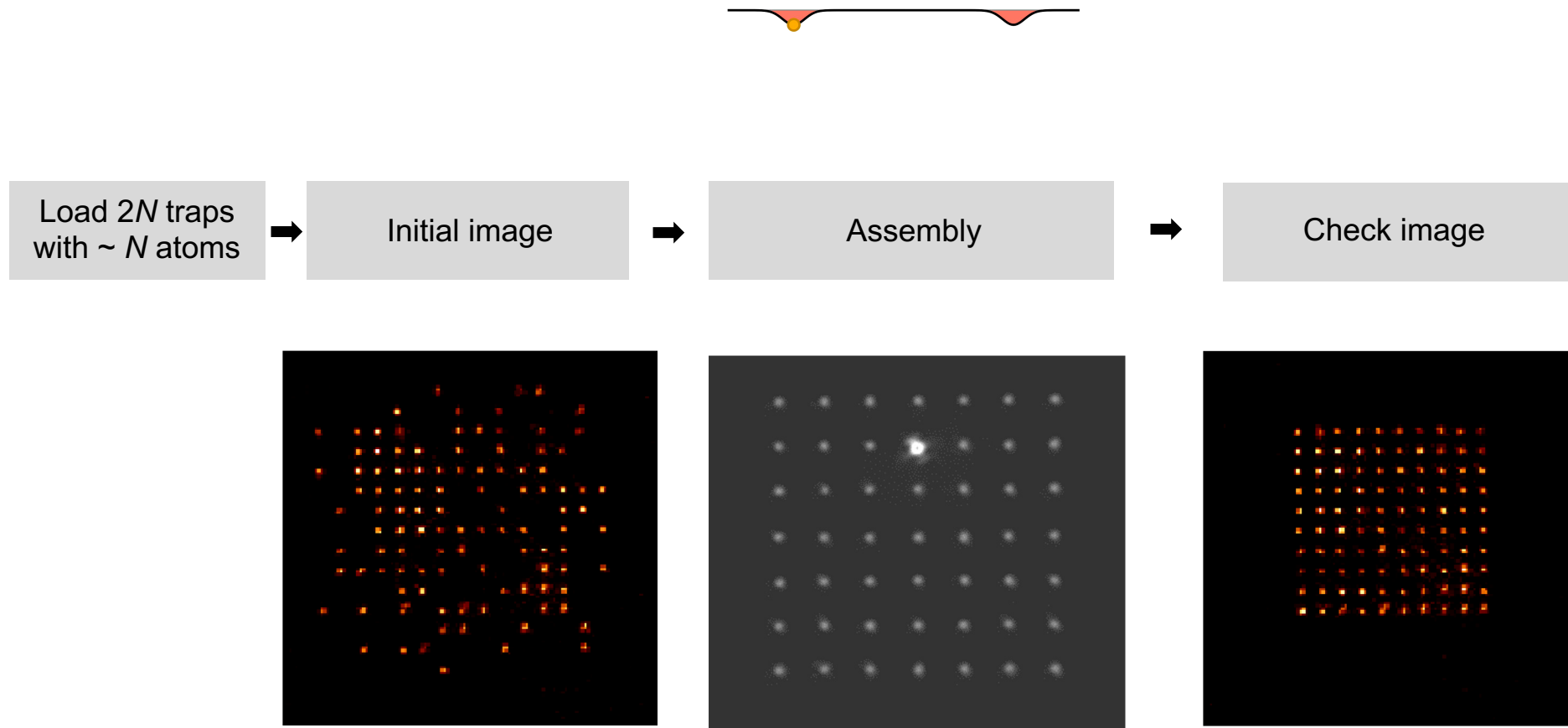
Barredo *et al.*, [Science](#) **354**, 1021 (2016)

See also:

Endres *et al.*, [Science](#) **354**, 1024 (2016)

Kim *et al.*, [Nature Comm.](#) **7**, 13317 (2016)

# Atom-by-atom assembly



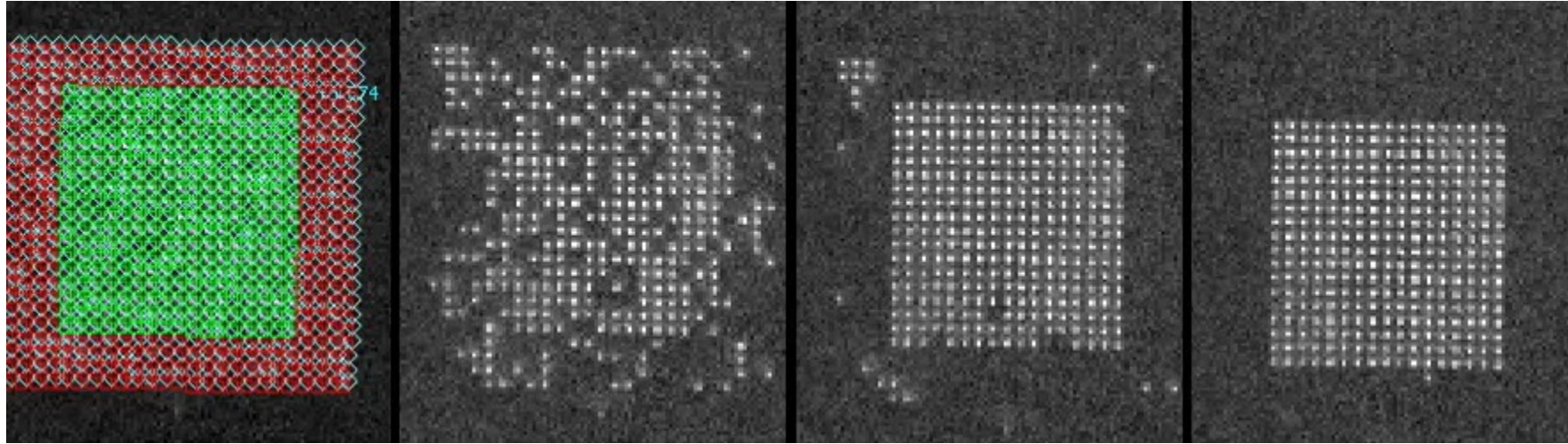
Barredo *et al.*, [Science](#) **354**, 1021 (2016)

See also:

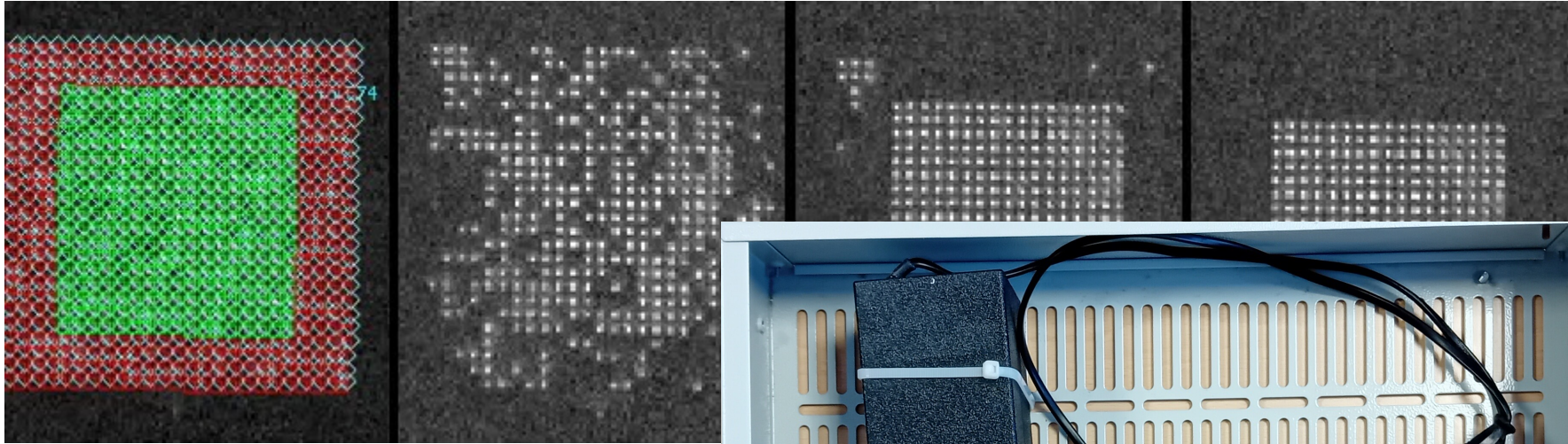
Endres *et al.*, [Science](#) **354**, 1024 (2016)

Kim *et al.*, [Nature Comm.](#) **7**, 13317 (2016)

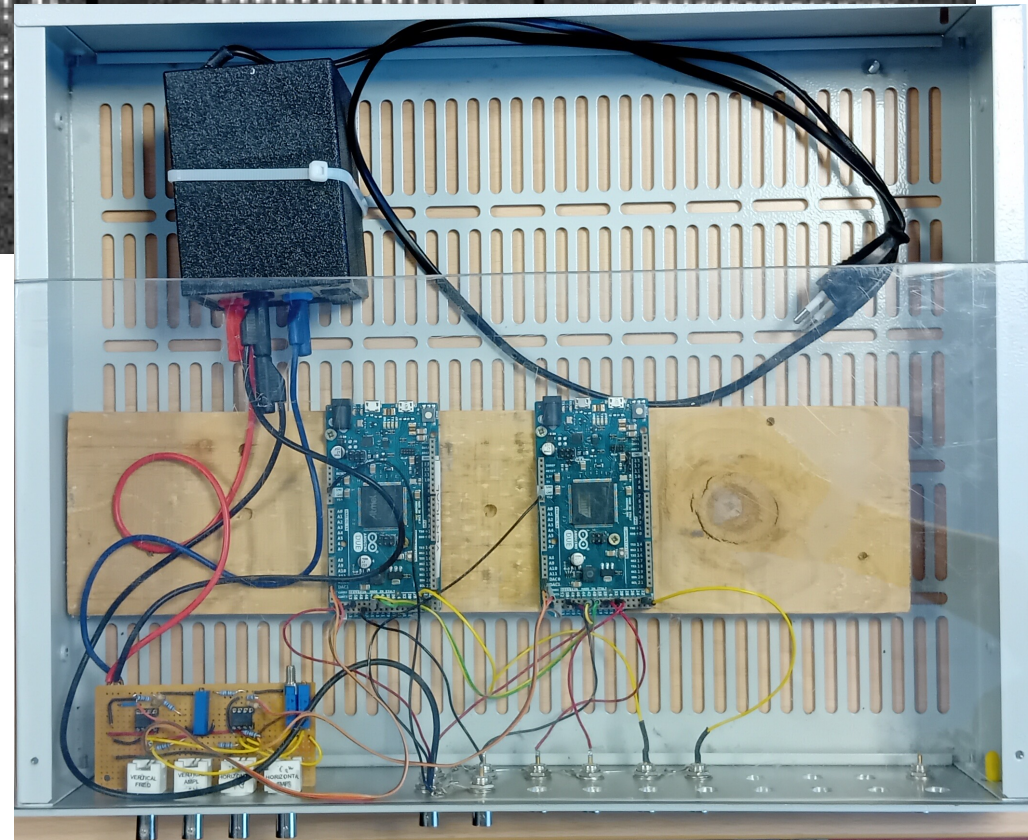
## *In practice in the lab*



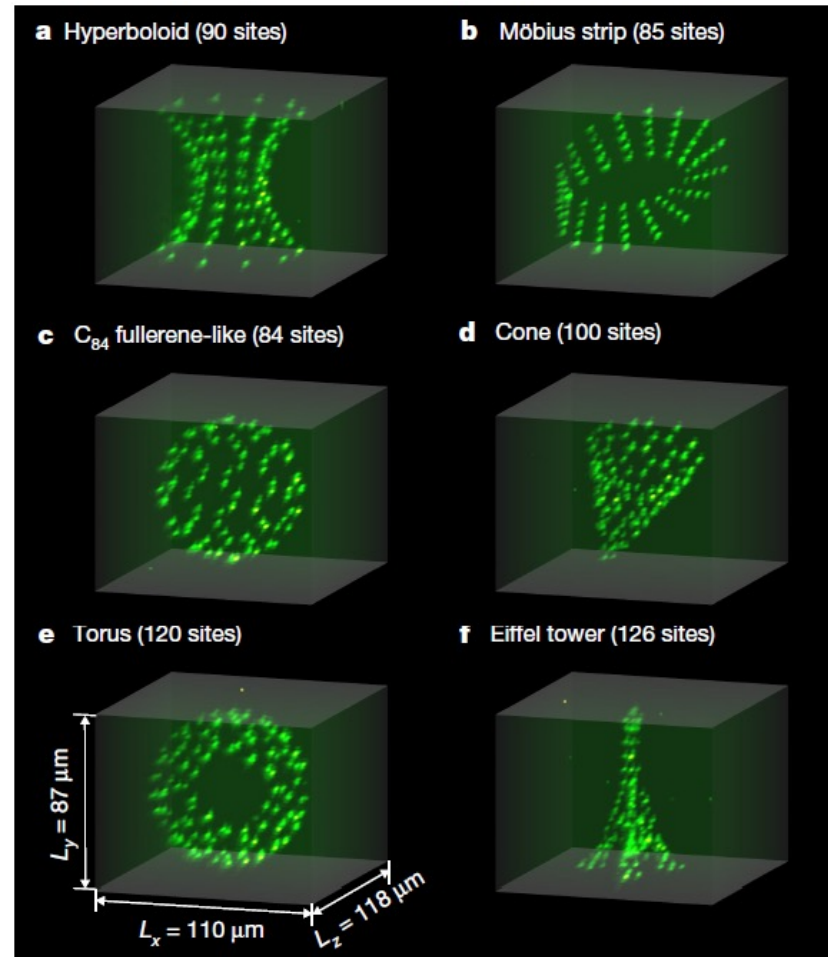
## *In practice in the lab*



- *Two Arduino boards driving cheap VCOs*
- *“quick and dirty test rig” that did all the work for 10+ years*



# Extension to 3D arrays

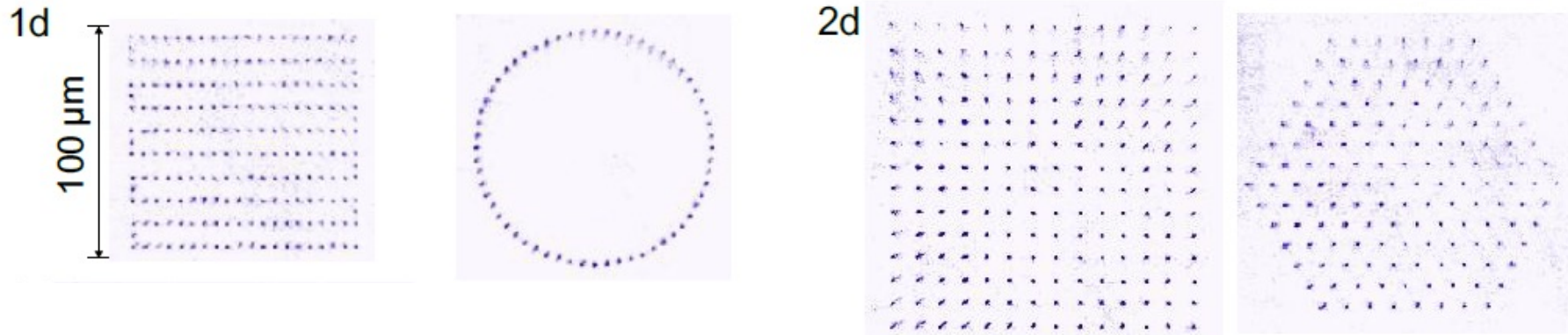


# Arbitrary geometries

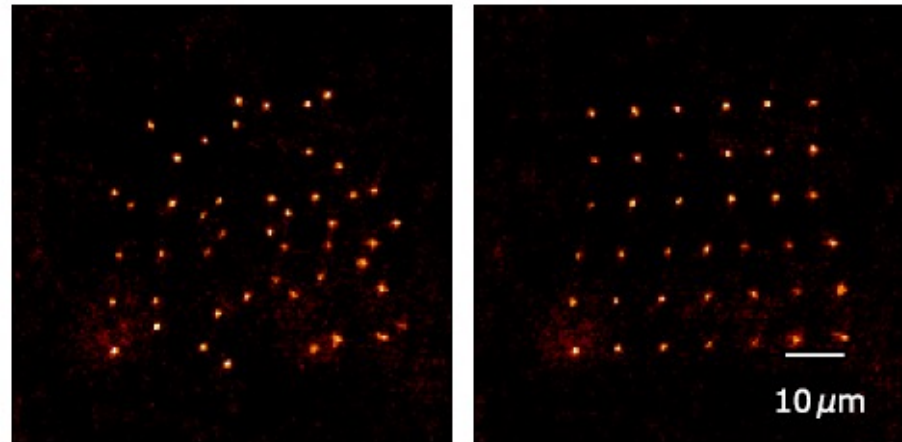
Improved assembler algorithms

K.-N. Schymik *et al.*, *Phys. Rev. A* **102**, 063107 (2020)

- **Up to > 200 atoms**



- **Geometries not limited to a regular array**



# Section 1

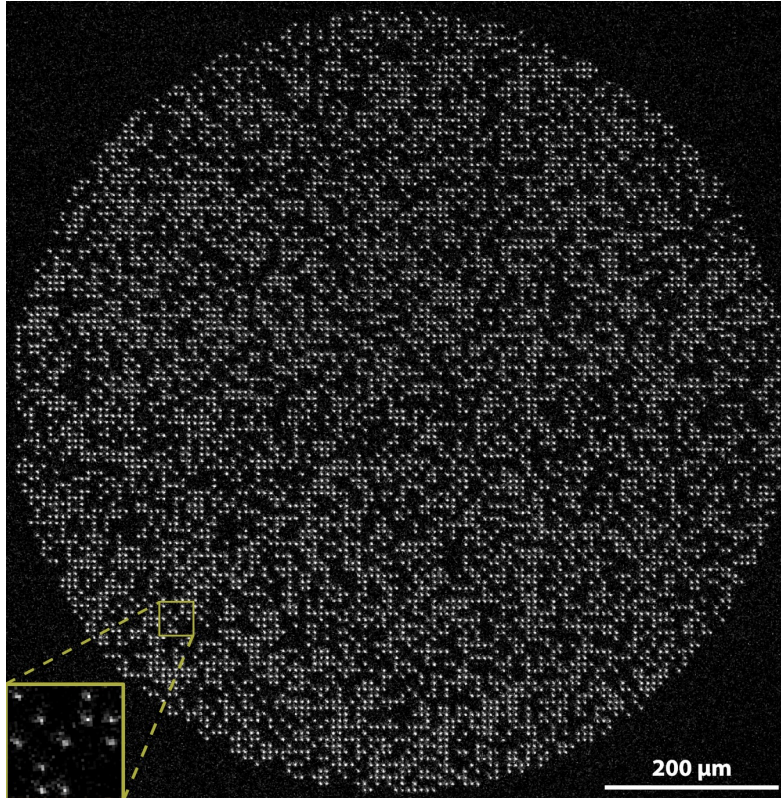
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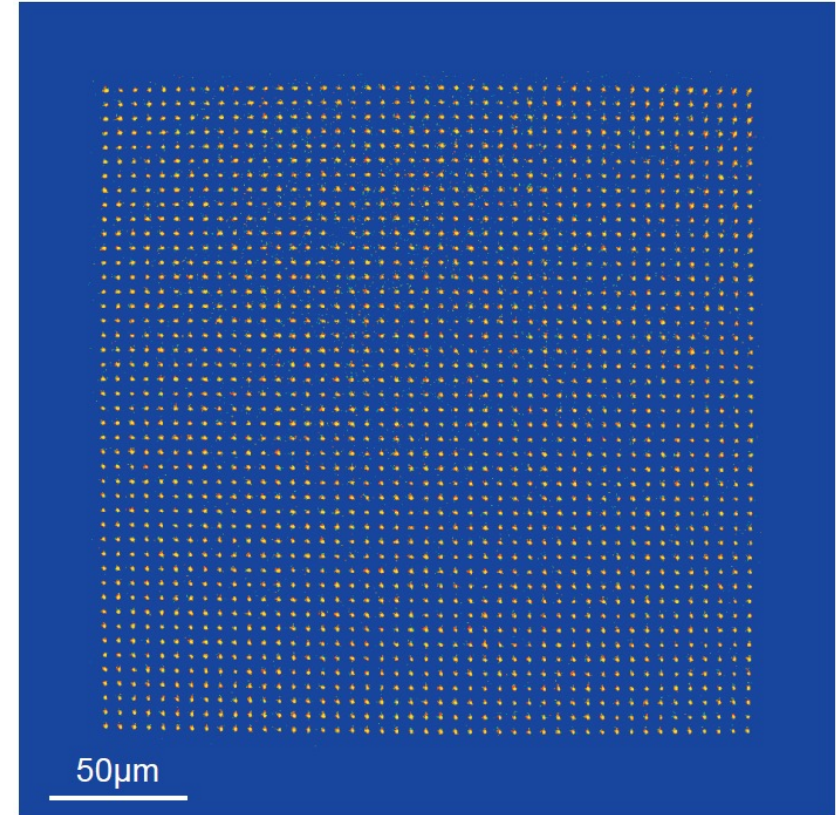
*3. Defect-free arrays*

**4. A few recent developments**

# Very large arrays



6100 qubits  
Endres group, Caltech



2024-atom rearranged array  
Pan group, Hefei

# Continuous reloading

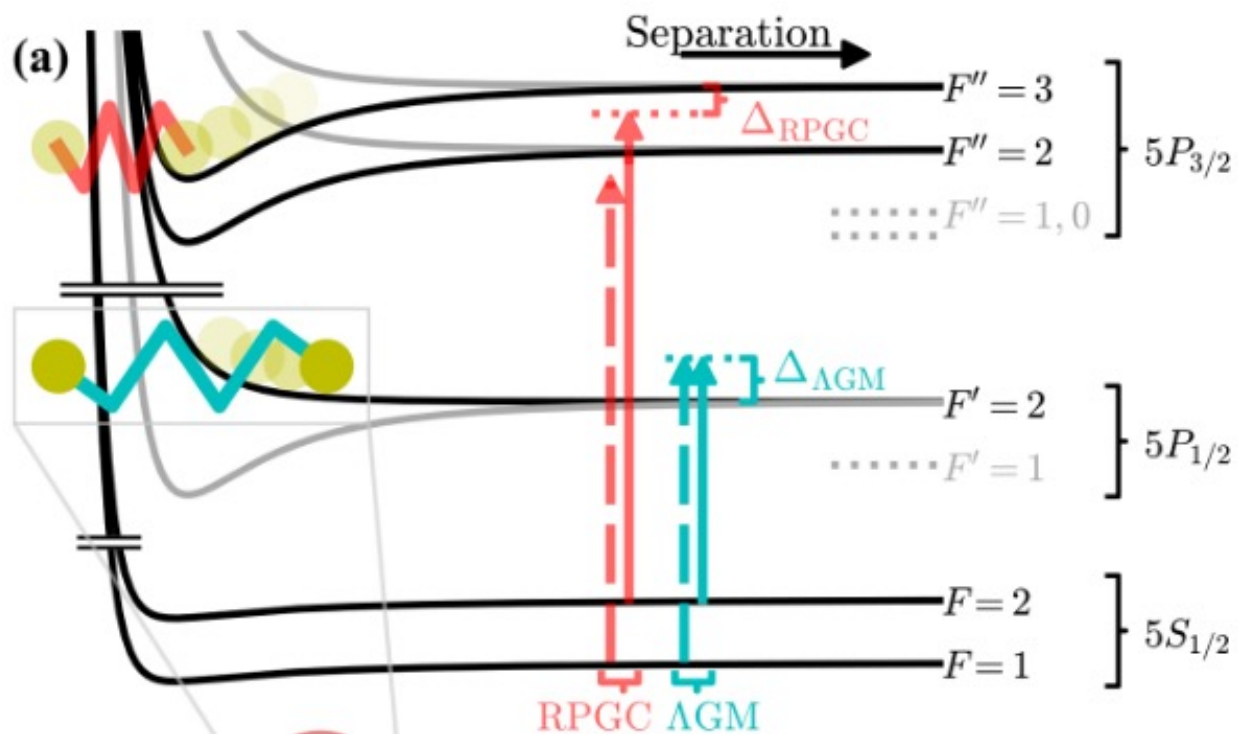


Lukin group, Harvard

Continuous operation of a coherent 3,000-qubit system

N-C Chiu *et al.*, [Nature](#) **646**, 1075 (2025)

# Enhanced loading with grey molasses

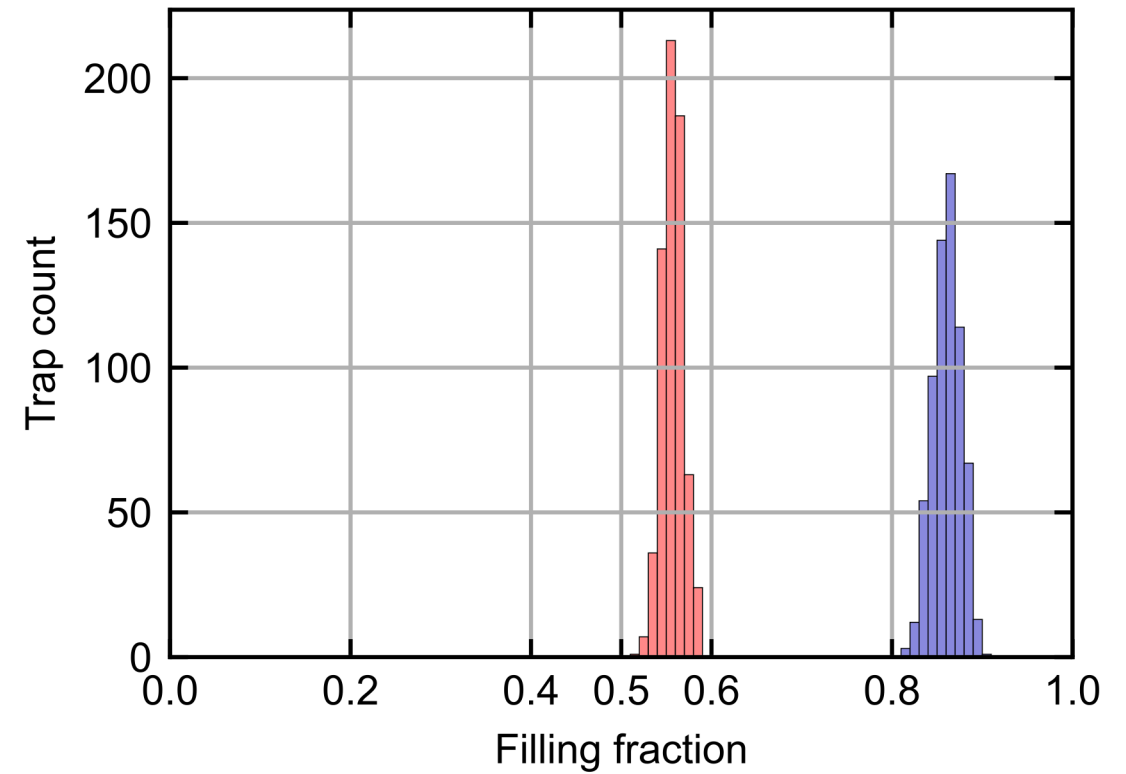
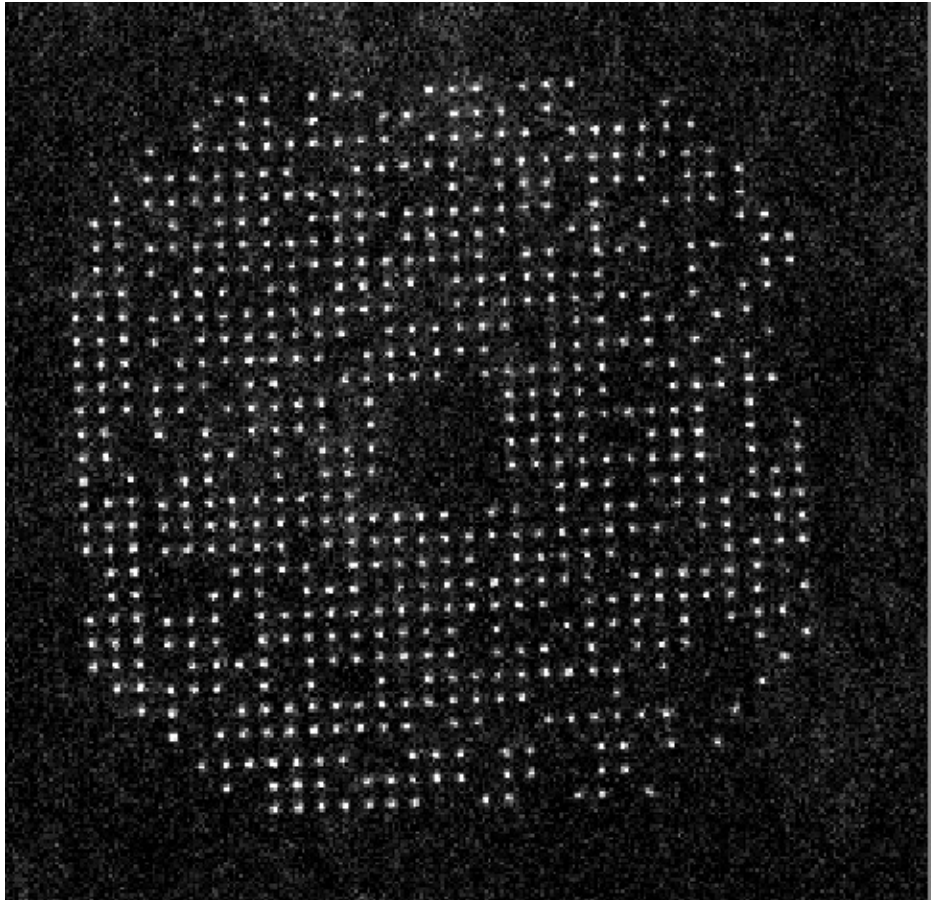


For  $\Delta < 2 U_{\text{tweezer}}$ , light-assisted collisions lead to the loss of a single atom!

Regal group, JILA  
Brown *et al.*, [PRX 9, 011057 \(2019\)](#)

Early work on blue-detuned collisions  
Andersen group, Otago

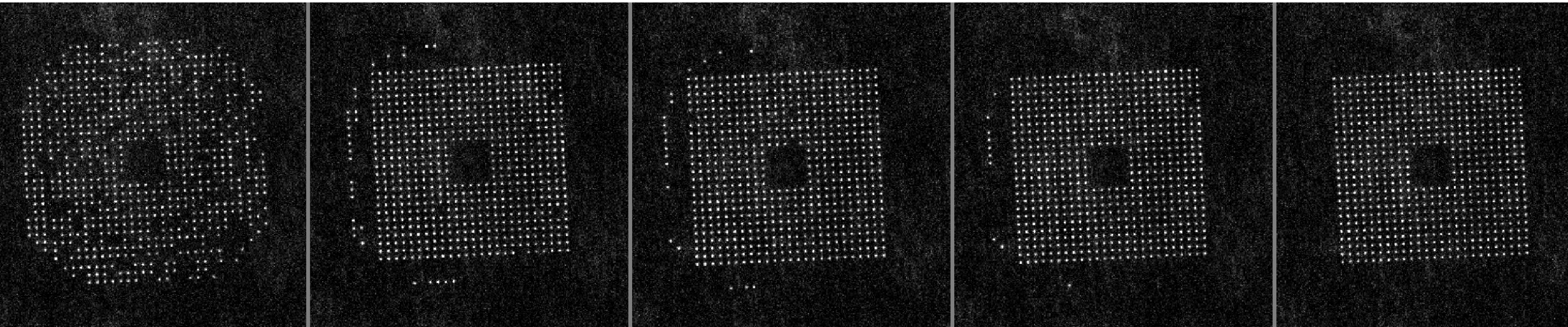
# *Enhanced loading in practice*



***85% loading efficiency  
instead of the usual 55%!***

# *600-atom array, defect-free*

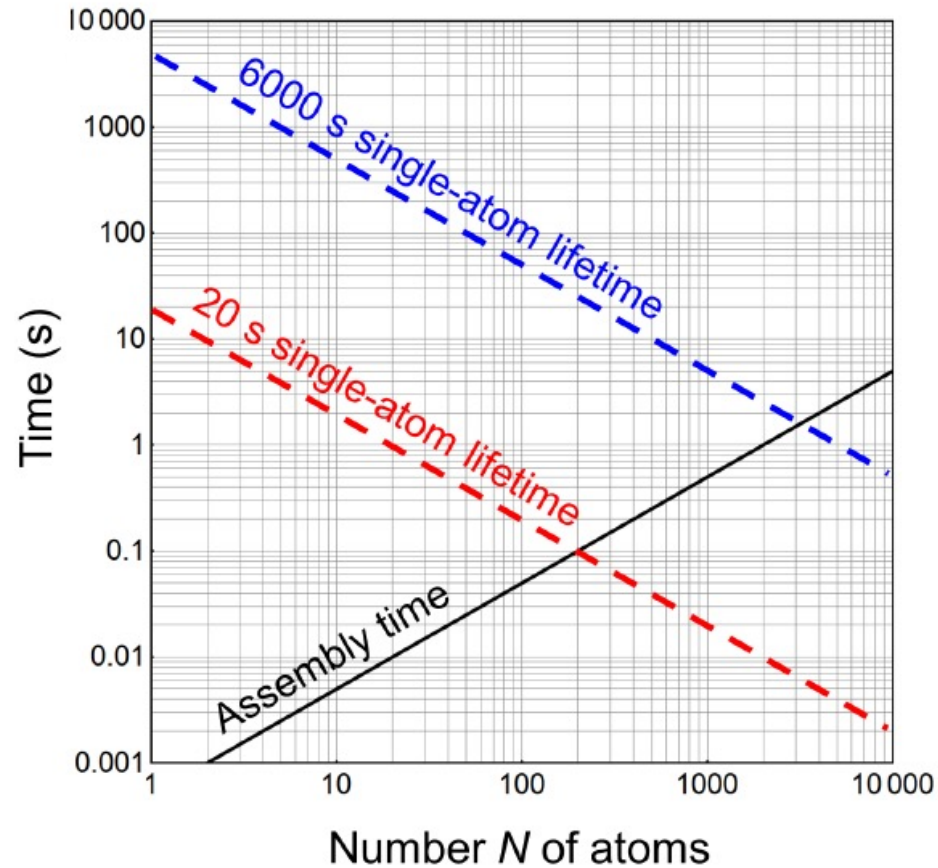
*4 rearrangements cycles*



# Cryogenic arrays: why?

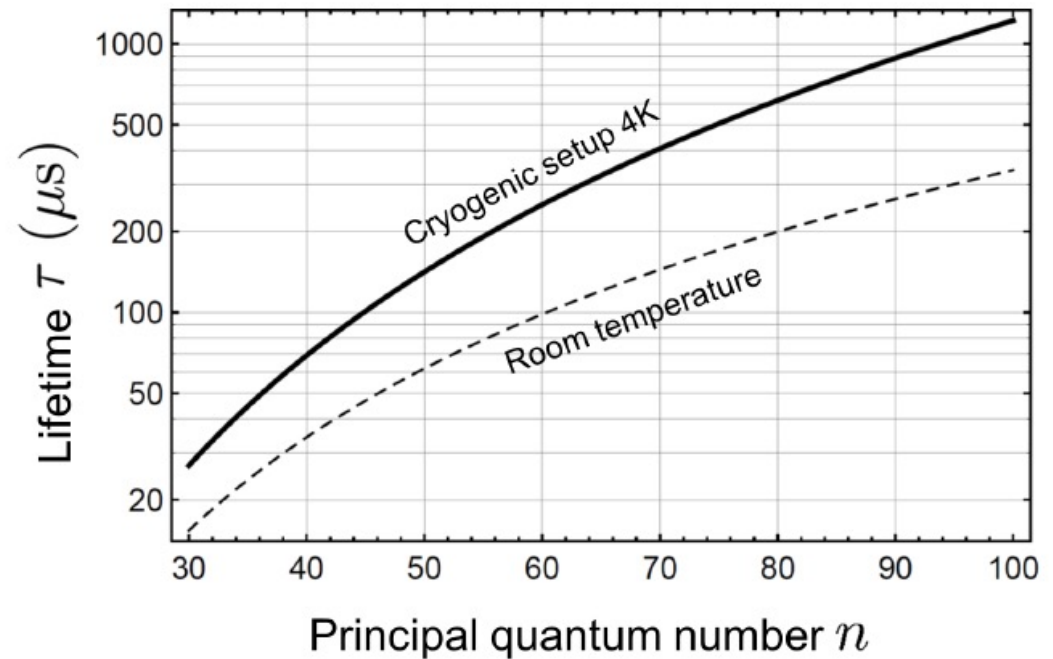
## **Better vacuum:**

More time for assembly without defects



## **No black-body radiation:**

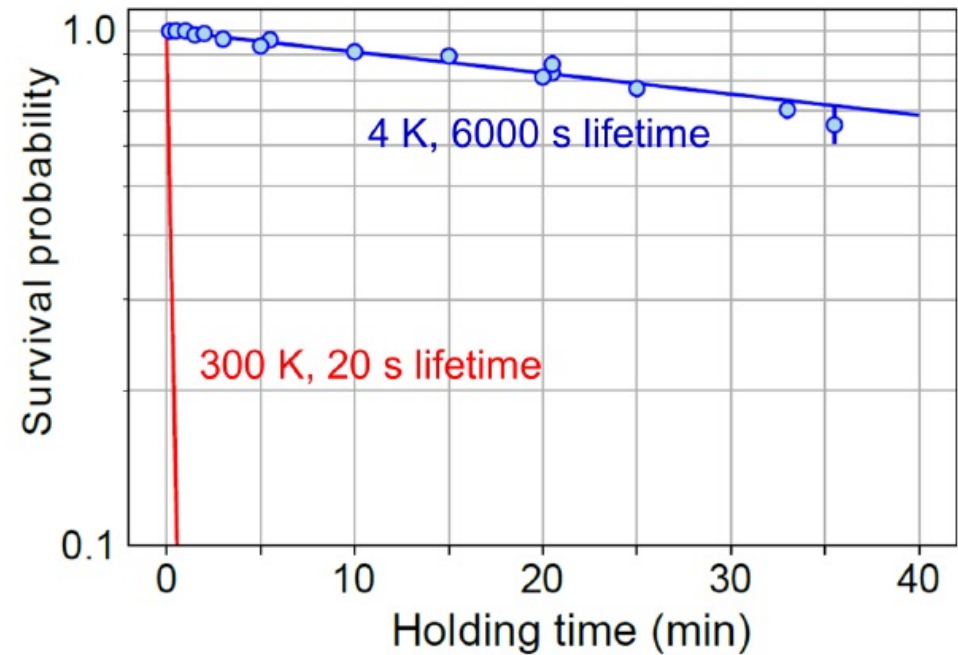
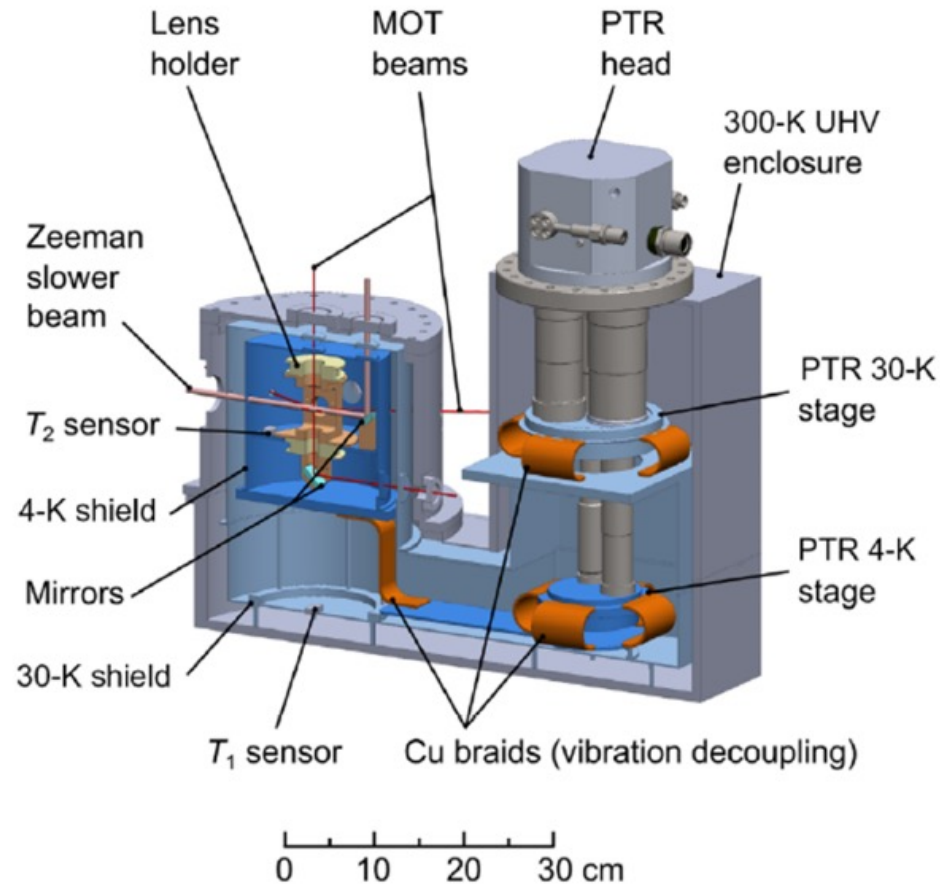
Longer Rydberg state lifetime



# Cryogenic arrays: first demo

Schymik *et al.*, *Phys. Rev. Applied* **16**, 034013 (2021)

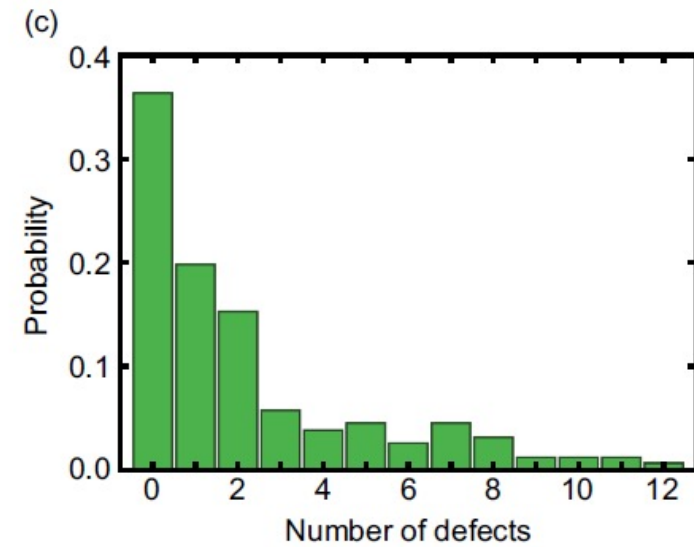
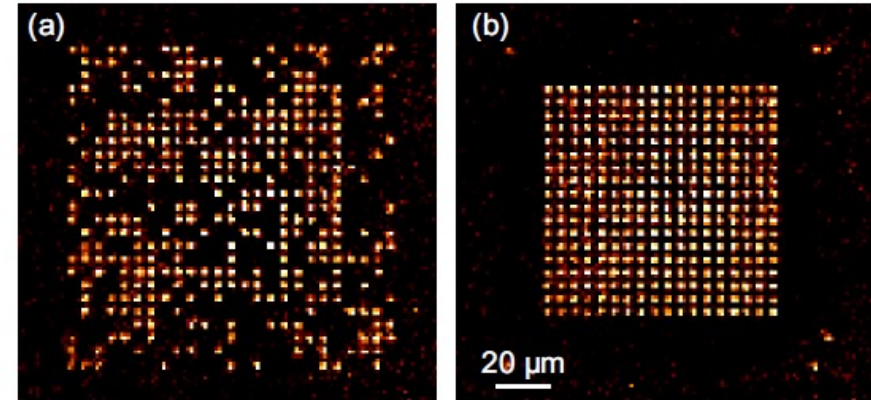
6000 s vacuum-limited lifetime in the tweezers!



# Cryogenic arrays: should be easy to go to large $N$ !

Schymik *et al.*, *Phys. Rev. A* **16**, 034013 (2022)

324 atoms (defect-free in 37% of shots)  
Limited by the small field of view of aspheric lens

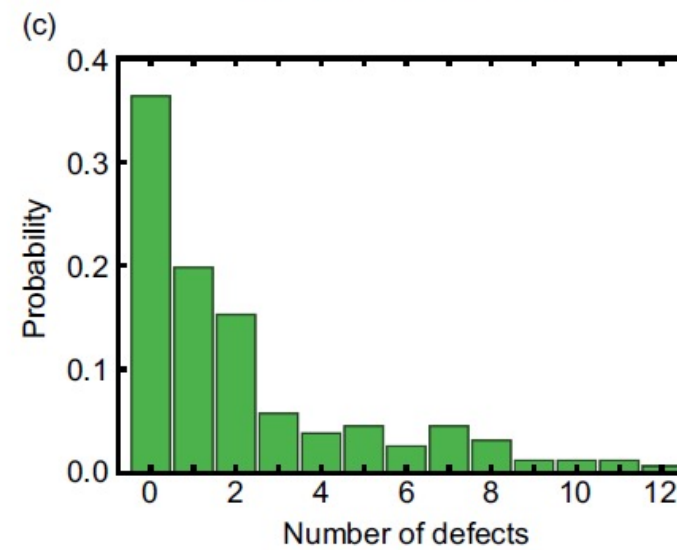
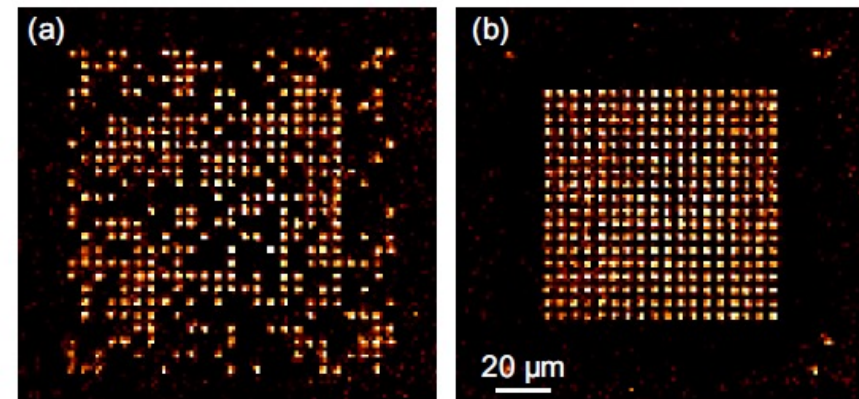


# Cryogenic arrays: should be easy to go to large $N$ !

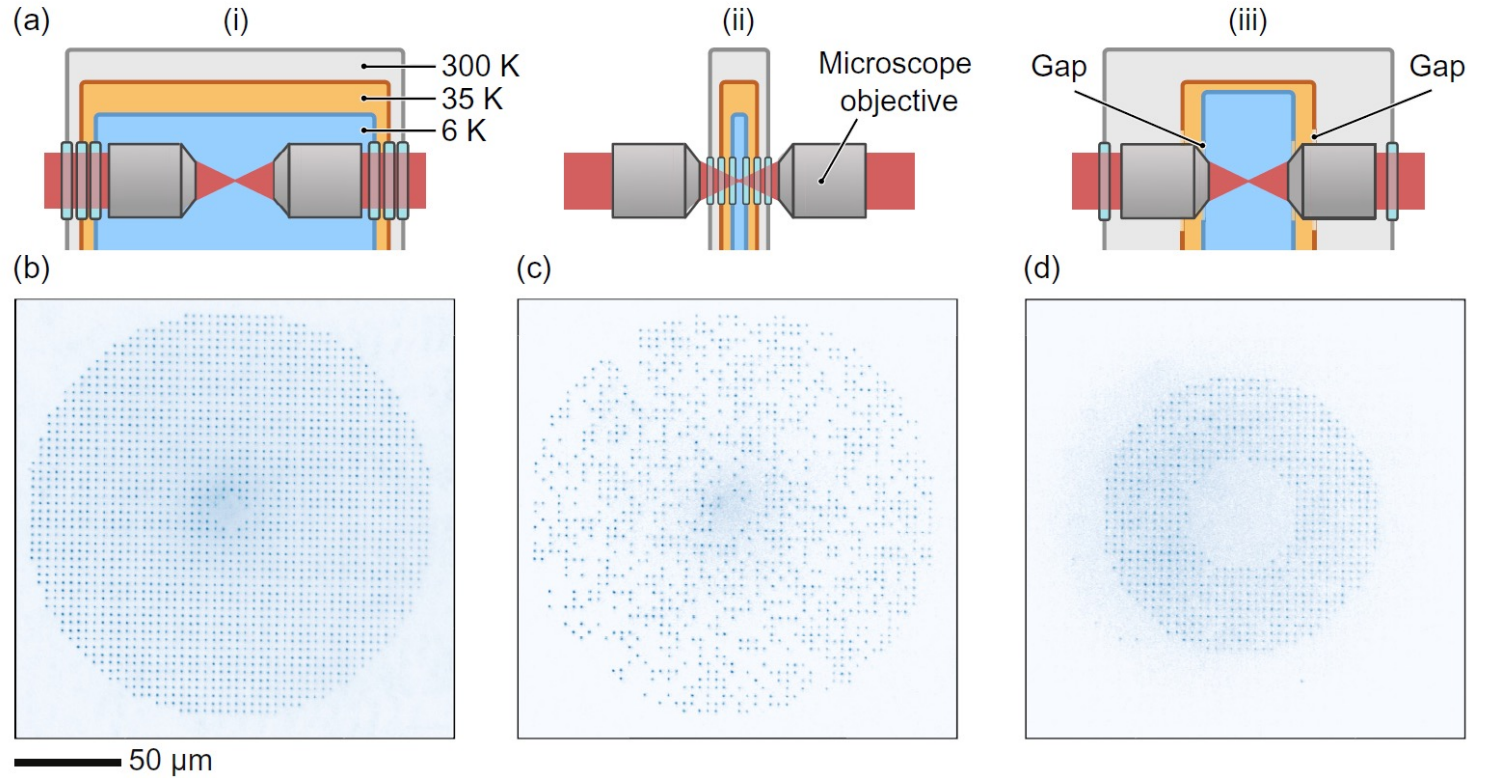
Schymik *et al.*, *Phys. Rev. A* **16**, 034013 (2022)

324 atoms (defect-free in 37% of shots)  
Limited by the small field of view of aspheric lens

***Go for microscope objectives!***



# Cryogenic arrays:

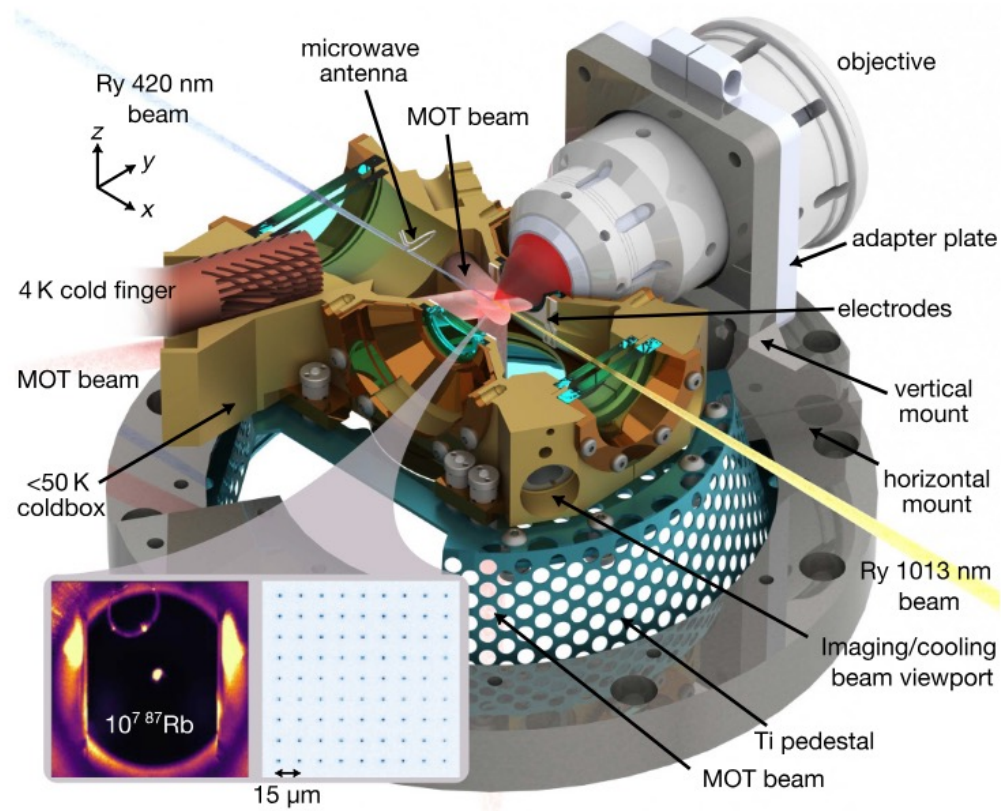


G. Pichard *et al.*,  
[Phys. Rev. Applied \*\*22\*\*, 024073 \(2024\)](#)

Microscope objectives  
~ 1000 atoms, but 5% defects

Lifetime only ~ 50s  
(gaps in the thermal shields)

# Cryogenic arrays



Regal group, JILA

Zhang *et al.*, [PRX Quantum 6, 020337 \(2025\)](#)

3000 s lifetime + Rydberg excitation

81 traps

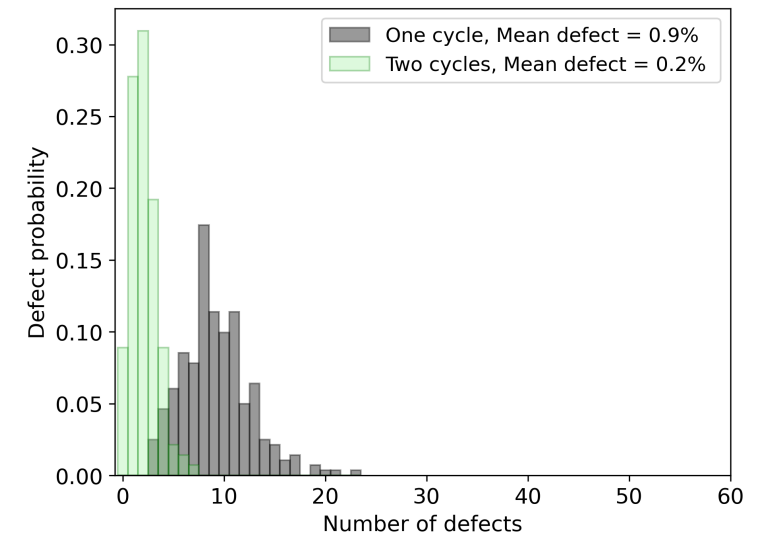
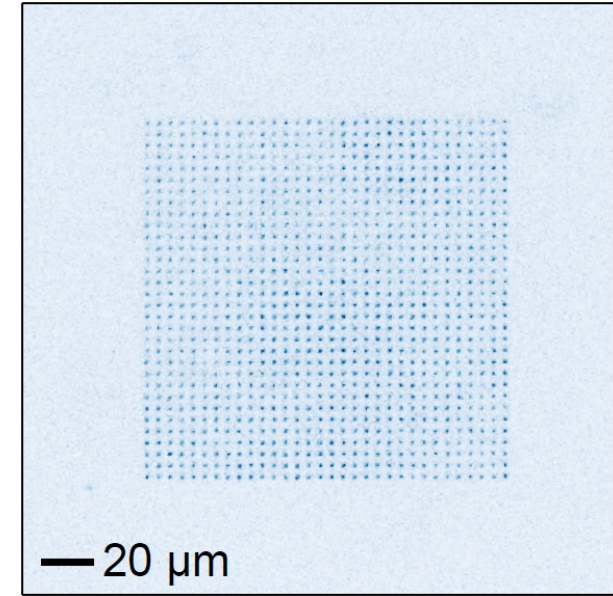
# Cryogenic arrays:

D. Lim *et al.*, [arXiv:2604.07205](https://arxiv.org/abs/2604.07205)

Microscope objectives + windows in 30K shield

Lifetime ~ 5000 s

1024 atoms, defect-free in 9% of the shots



## ***Section 2***

***1. Rydberg atoms***

***2. Interactions between Rydberg atoms***

# ***Section 2***

## ***1. Rydberg atoms***

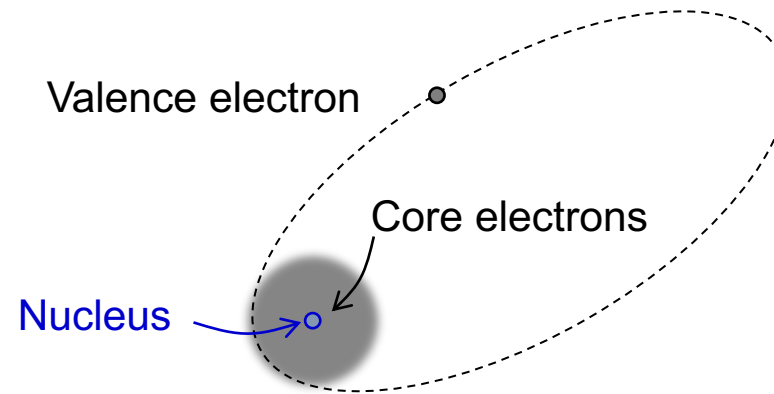
## *2. Interactions between Rydberg atoms*

# Rydberg atoms



Johannes Rydberg  
1854-1919

Atoms in a highly excited state with a very large principal quantum number  $n$ .



## ***Exaggerated properties:***

- Large size, long lifetime
- Strong interactions with external fields (E-fields, MW...)
- Strong ***interactions*** between atoms

# Three “golden ages” of Rydberg atoms

*Spectroscopy & Early QM*

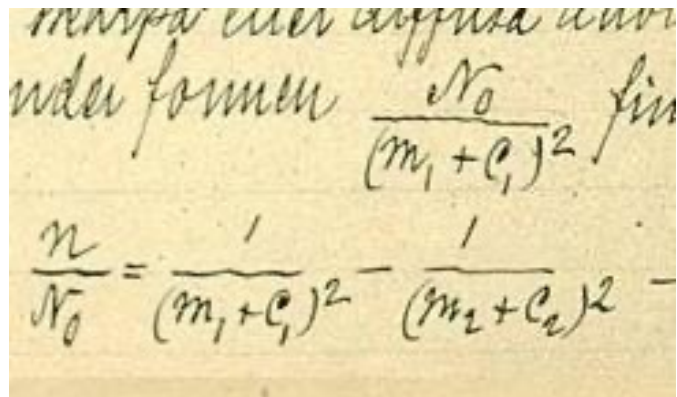
**1890**

Rydberg

Bohr

Fermi

Segrè...



Handwritten manuscript snippet showing the Rydberg formula:

$$\frac{n}{N_0} = \frac{1}{(m_1 + c_1)^2} - \frac{1}{(m_2 + c_2)^2}$$

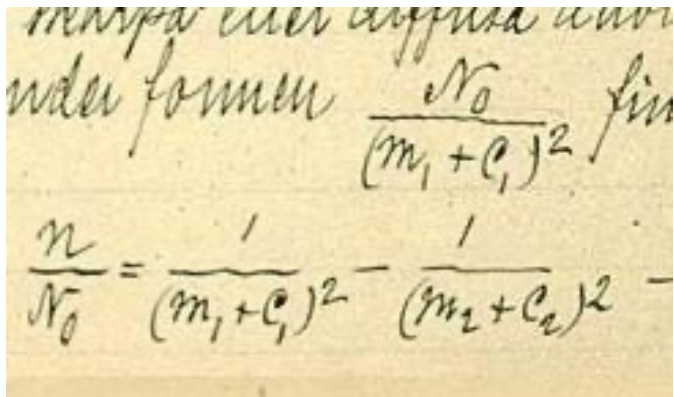
# Three “golden ages” of Rydberg atoms

*Spectroscopy & Early QM*

*Tunable lasers: atom-light interaction*

**1890**

Rydberg  
Bohr  
Fermi  
Segrè...

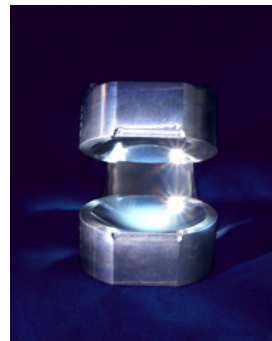


Handwritten mathematical formula on aged paper:

$$\frac{n}{N_0} = \frac{1}{(m_1 + c_1)^2} - \frac{1}{(m_2 + c_2)^2}$$

**~1975**

Kleppner  
Gallagher  
Walther  
Haroche...



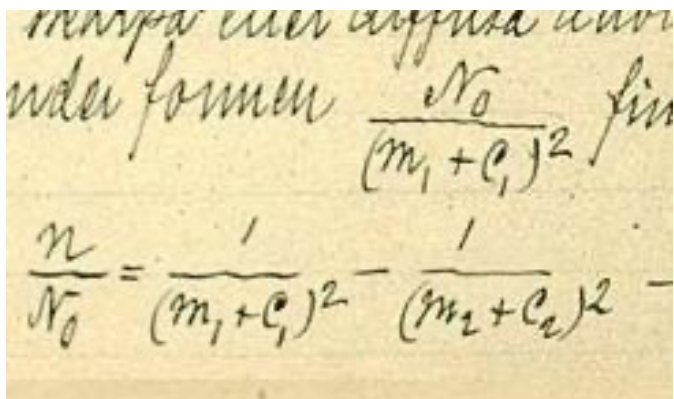
# Three “golden ages” of Rydberg atoms

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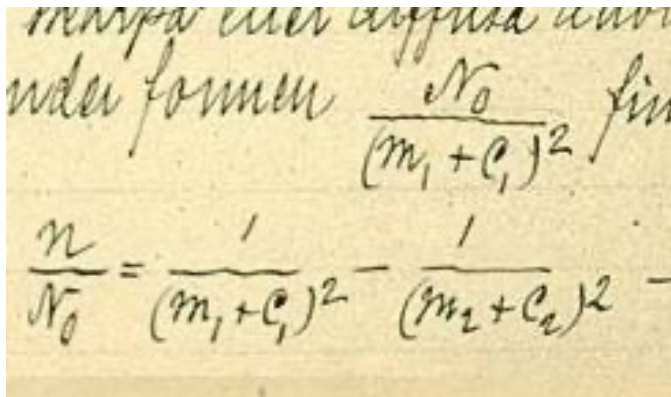
*Spectroscopy & Early QM*

*Tunable lasers: atom-light interaction*

*Cold Rydberg atoms*

**1890**

Rydberg  
Bohr  
Fermi  
Segrè...

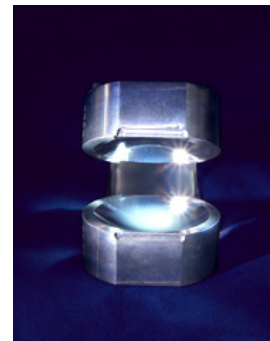


Handwritten mathematical formula on aged paper:

$$\frac{n}{N_0} = \frac{1}{(m_1 + c_1)^2} - \frac{1}{(m_2 + c_2)^2}$$

**~1975**

Kleppner  
Gallagher  
Walther  
Haroche...



**~2000**

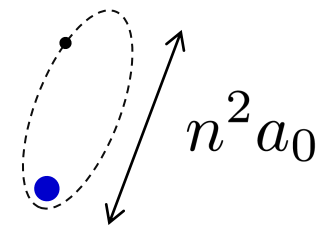
Gallagher  
Pillet  
Gould  
Weidemüller  
Pfau  
Saffman  
Grangier/Browaeys  
Adams  
Bloch...

And many others !



# Rydberg atoms

Large principal quantum number:  $n \gg 1$   
 $n \sim 50 - 100$



Energies  $E_n = \frac{-13.6 \text{ eV}}{(n - \delta_{nlj})^2} \sim \frac{1}{n^2}$

## ***Exaggerated properties:***

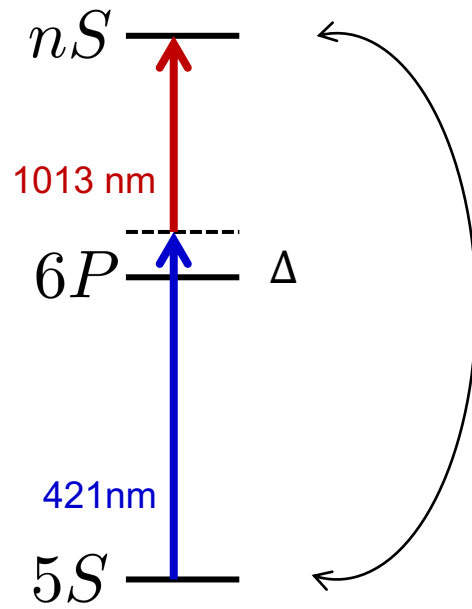
Electric dipole  $\langle nS | d | nP \rangle \sim n^2$

Lifetime  $\tau \sim n^3$  (hundreds of  $\mu\text{s}$ )

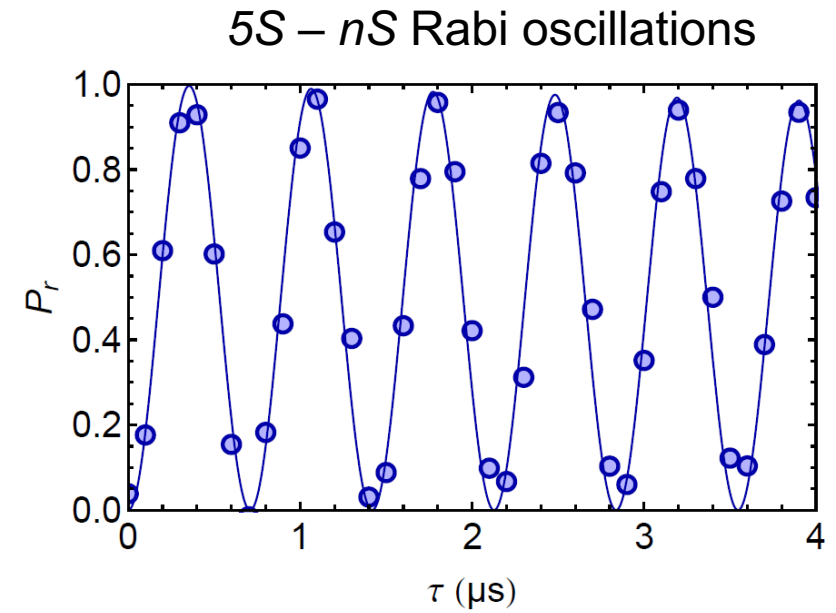
Polarizability  $\alpha \sim n^7$

Interactions  $V_{\text{dd}} \sim n^4$   $V_{\text{vdW}} \sim n^{11}$

# Rydberg excitation



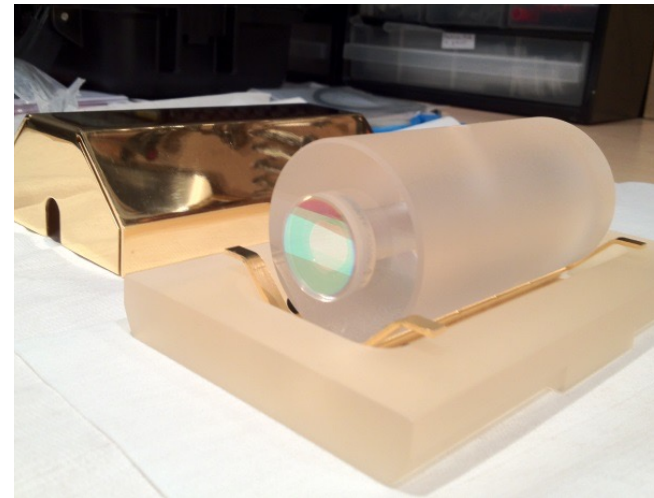
$$\Omega_{\text{eff}} = \frac{\Omega_1 \Omega_2}{2\Delta}$$



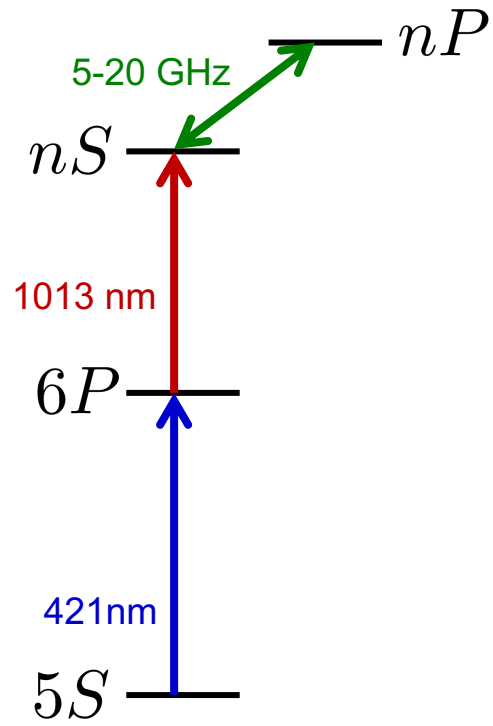
## *In practice*



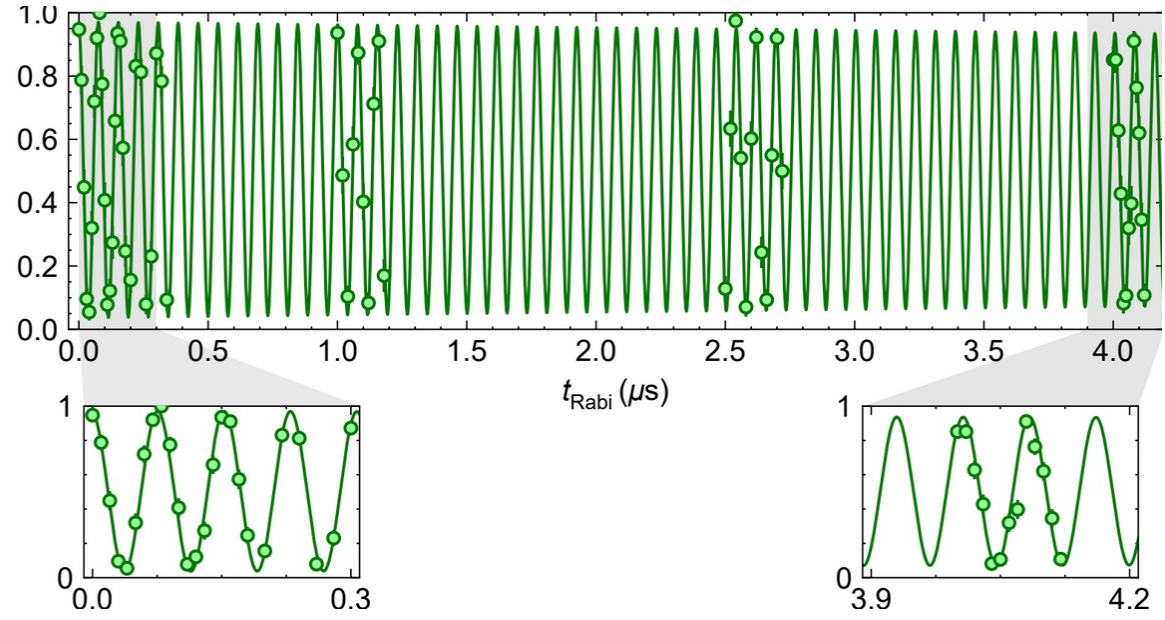
- Several watts on the atoms
- Frequency controlled to better than 10 kHz
- Low phase noise
- Ultra-stable cavity (finesse = 20 000, length fluctuations below  $10^{-12}$  m)



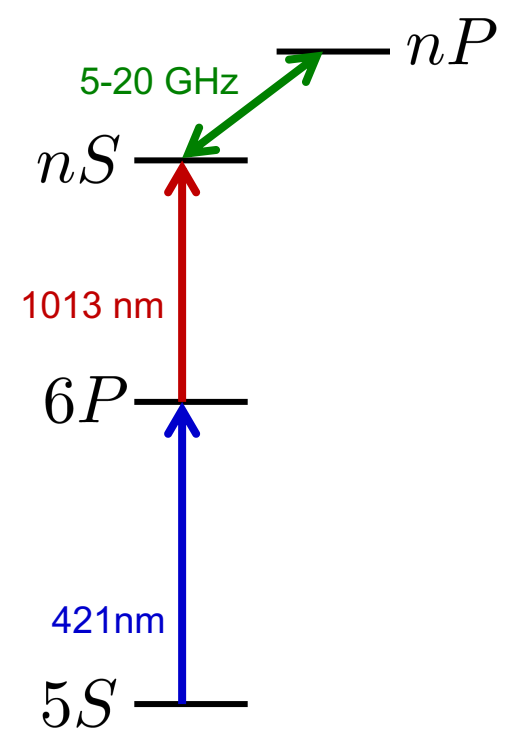
# Rydberg excitation and microwave manipulations



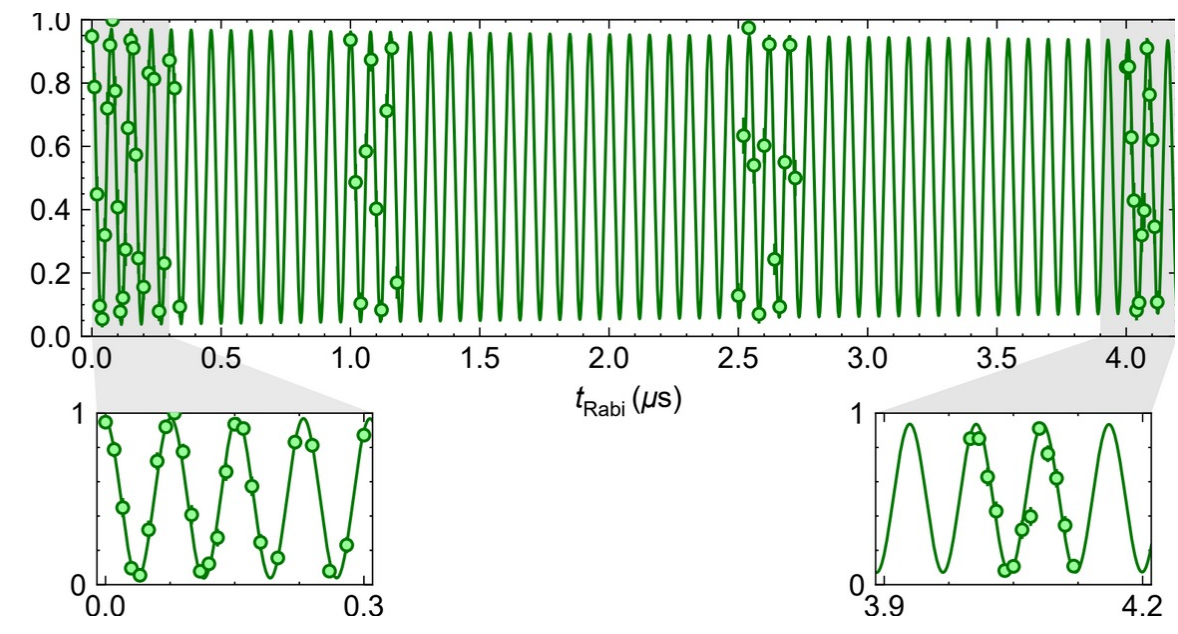
60S – 60P transition at 16.7 GHz



# Rydberg excitation and microwave manipulations



60S – 60P transition at 16.7 GHz

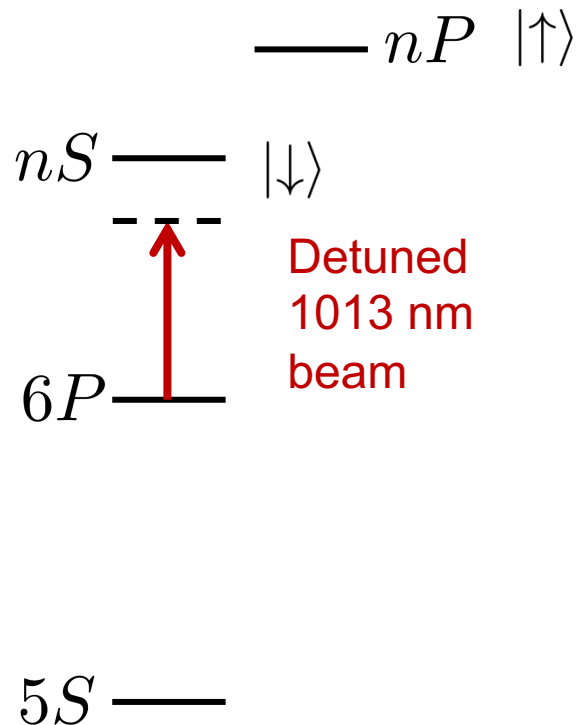


# Optical addressing

Microwave manipulations are **global** ( $\lambda \sim \text{cm}$ )

$\Rightarrow$  **use local light shifts to address atoms with an array**

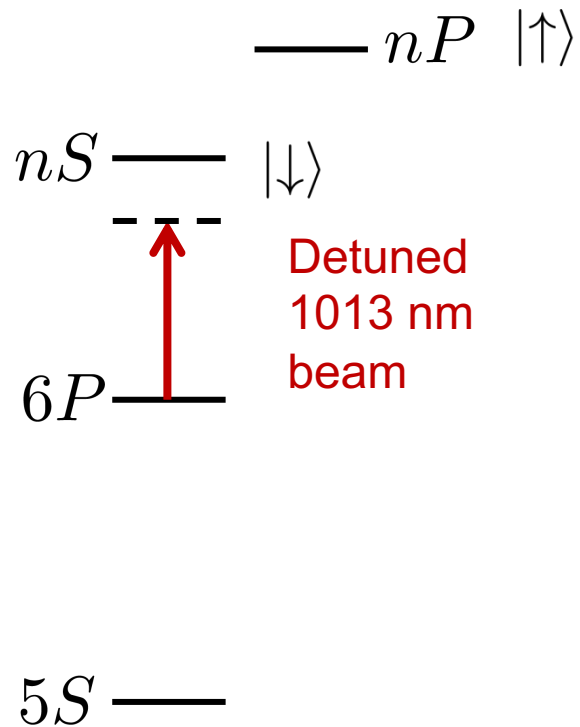
- First experiments with a *single beam*:  
S. de Léséleuc *et al.*, [PRL \*\*119\*\*, 053202 \(2017\)](#)



# Optical addressing

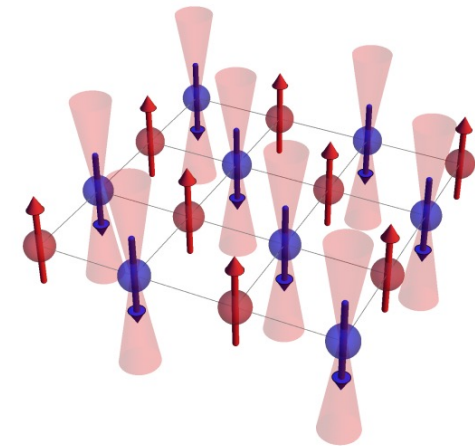
Microwave manipulations are **global** ( $\lambda \sim \text{cm}$ )

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S. de Léséleuc *et al.*, [PRL \*\*119\*\*, 053202 \(2017\)](#)

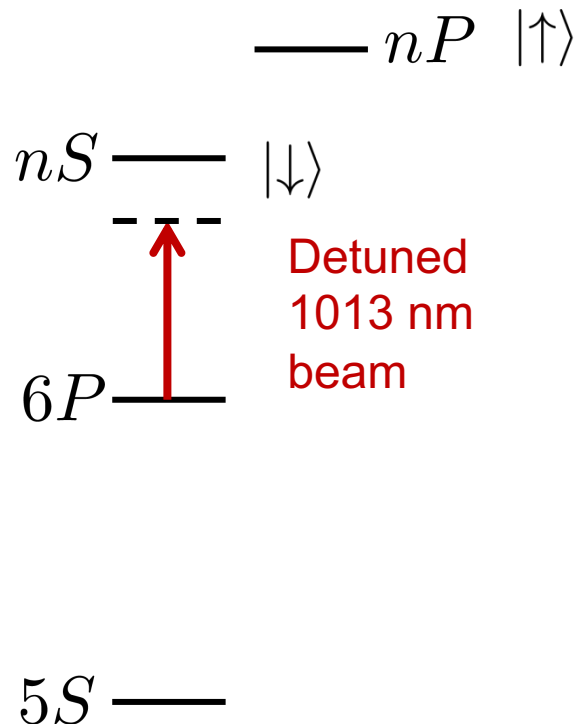
- Adding an SLM: spatial control  
(but time dependence is global)



# Optical addressing

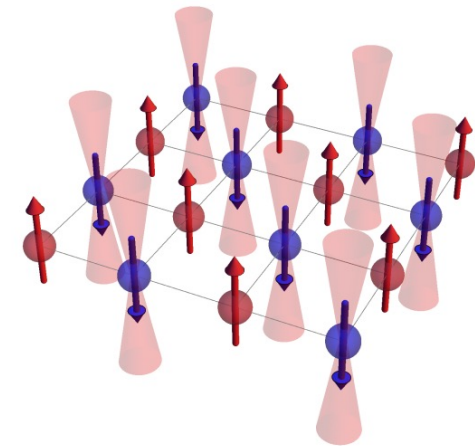
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- First experiments with a *single beam*:  
S. de Léséleuc *et al.*, [PRL \*\*119\*\*, 053202 \(2017\)](#)

- Adding an SLM: spatial control  
(but time dependence is global)



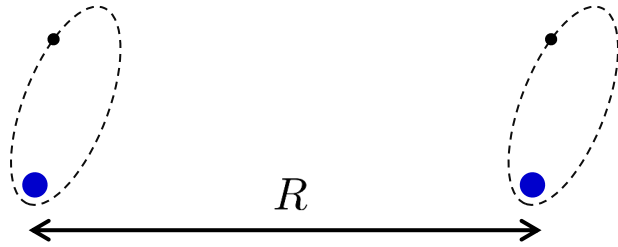
- Use several values of light-shift and multi-tone microwaves  
G. Bornet *et al.*, [Phys. Rev. Lett. \*\*132\*\*, 263601 \(2024\)](#).

# **Section 2**

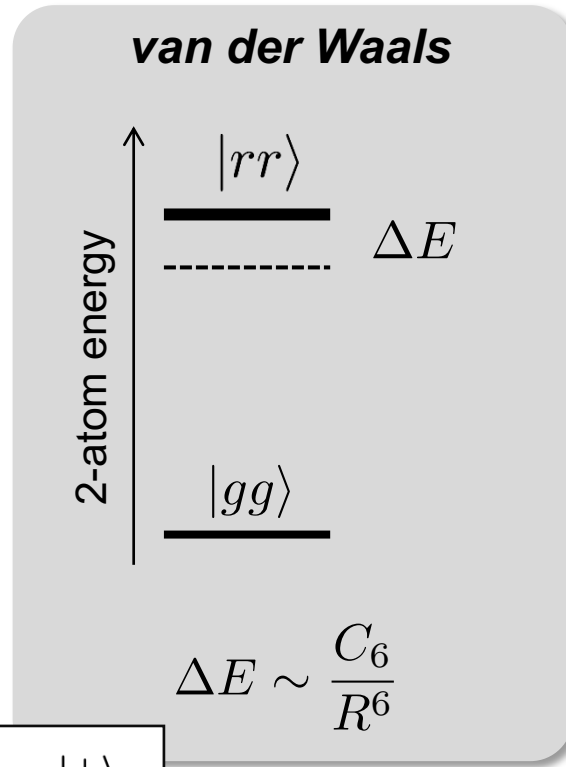
*1. Rydberg atoms*

***2. Interactions between Rydberg atoms***

# Interactions between Rydberg states



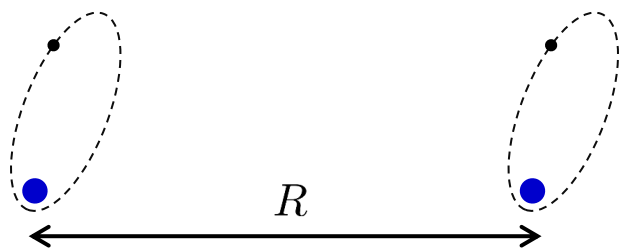
$$\hat{V}_{\text{ddi}} = \frac{1}{4\pi\epsilon_0} \frac{\hat{\mathbf{d}}_1 \cdot \hat{\mathbf{d}}_2 - 3(\hat{\mathbf{d}}_1 \cdot \hat{\mathbf{n}})(\hat{\mathbf{d}}_2 \cdot \hat{\mathbf{n}})}{R^3}$$



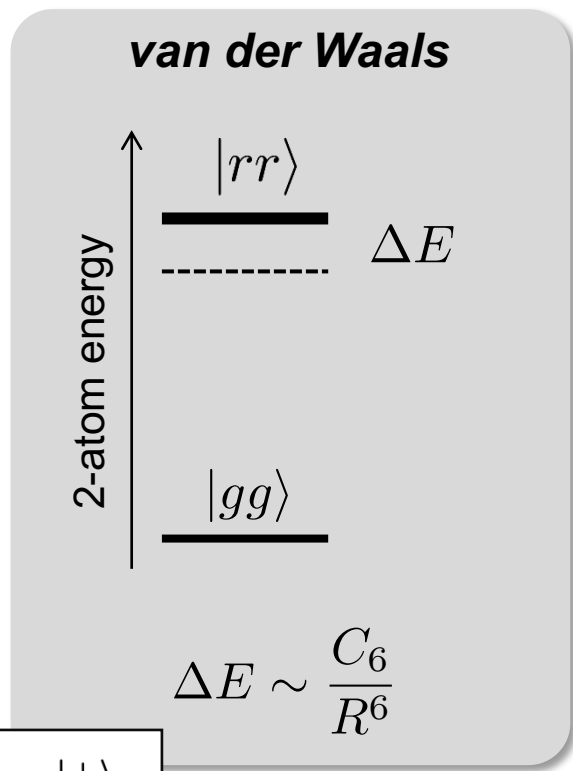
$$\begin{cases} |g\rangle \rightarrow |\downarrow\rangle \\ |r\rangle \rightarrow |\uparrow\rangle \end{cases}$$

Ising-like interaction

# Interactions between Rydberg states

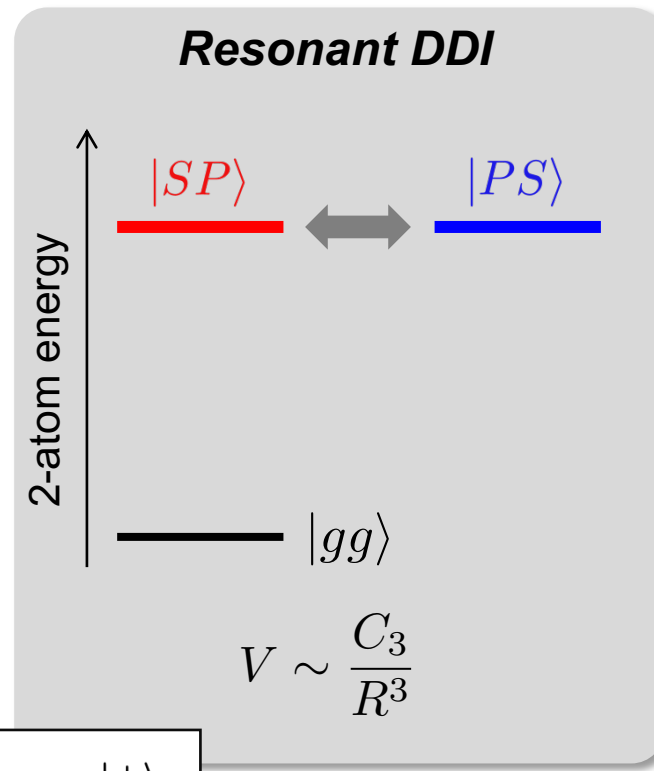


$$\hat{V}_{\text{ddi}} = \frac{1}{4\pi\epsilon_0} \frac{\hat{\mathbf{d}}_1 \cdot \hat{\mathbf{d}}_2 - 3(\hat{\mathbf{d}}_1 \cdot \hat{\mathbf{n}})(\hat{\mathbf{d}}_2 \cdot \hat{\mathbf{n}})}{R^3}$$



$$\begin{cases} |g\rangle \rightarrow |\downarrow\rangle \\ |r\rangle \rightarrow |\uparrow\rangle \end{cases}$$

Ising-like interaction

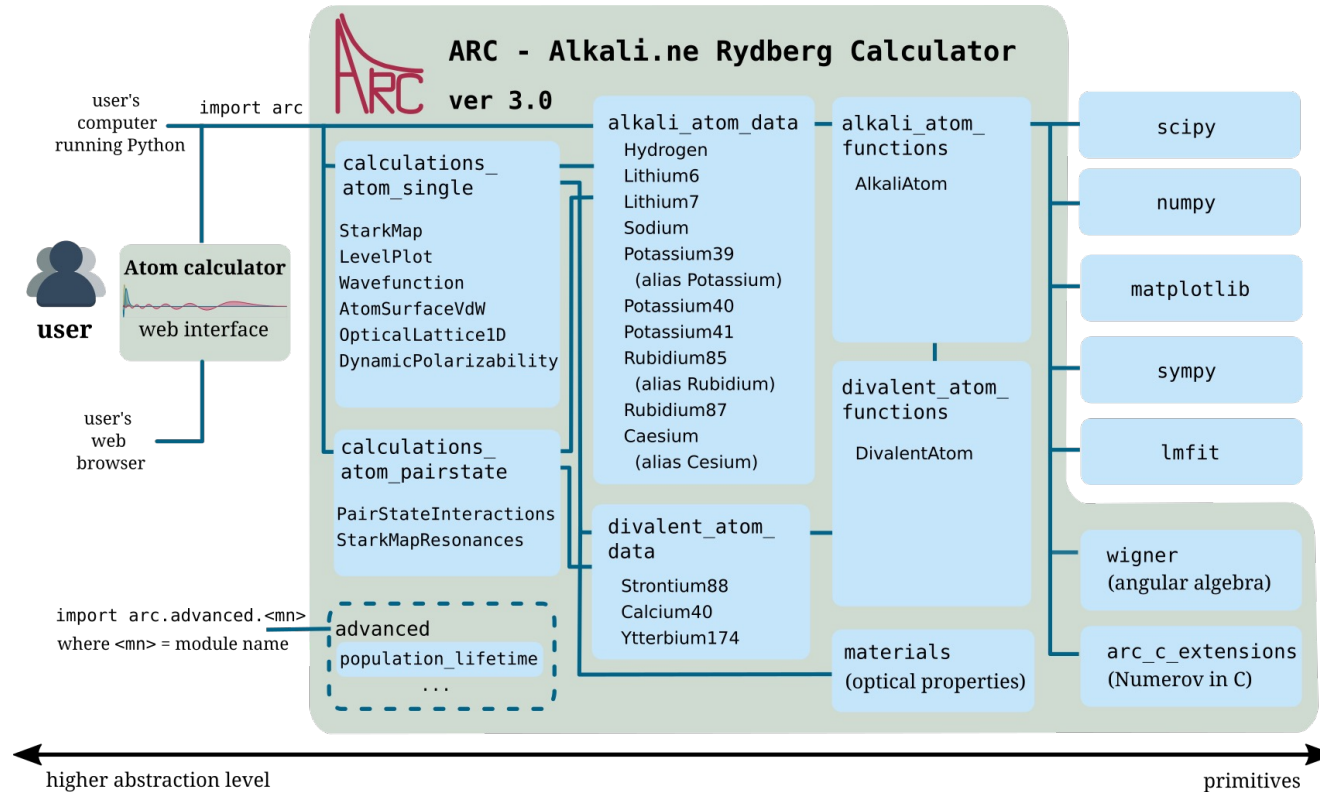


$$\begin{cases} |S\rangle \rightarrow |\downarrow\rangle \\ |P\rangle \rightarrow |\uparrow\rangle \end{cases}$$

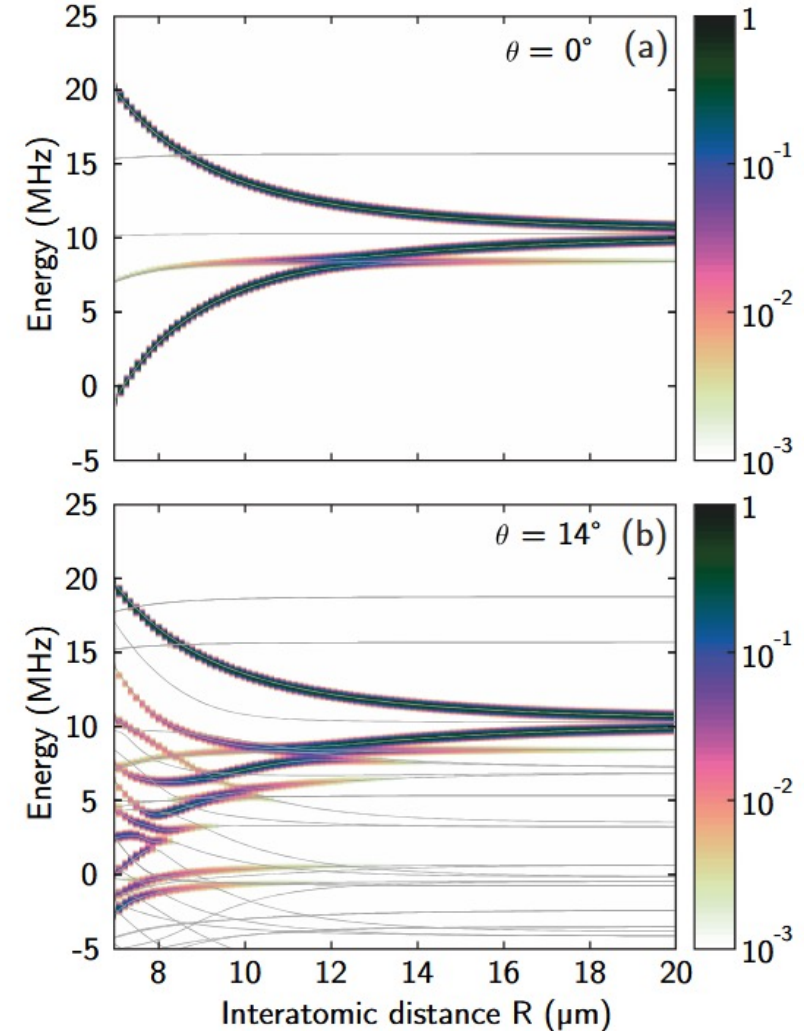
XY interaction (flip-flop)

# Python packages to calculate interactions

ARC  
Nikola Sibalic *et al*, Durham

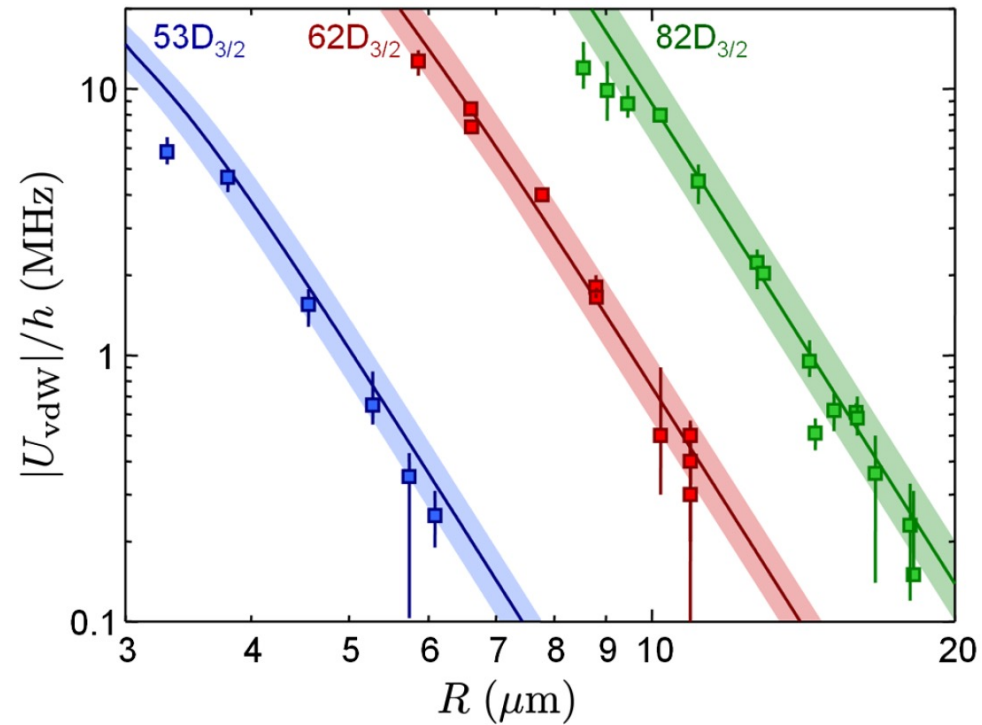
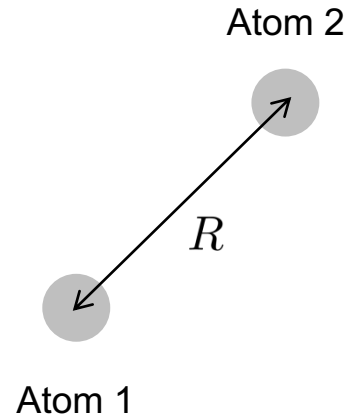


Pair Interactions  
Sebastian Weber *et al*, Stuttgart



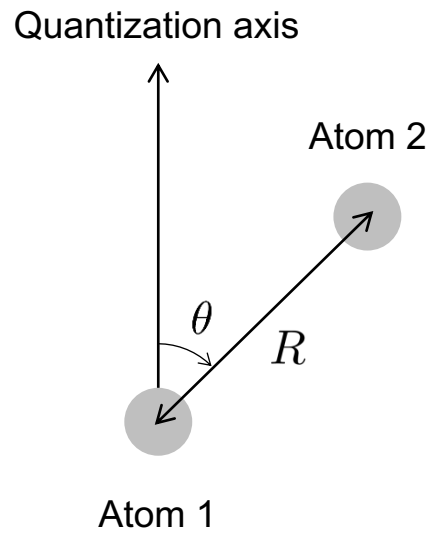
# Measuring the van der Waals interaction

L. Béguin *et al.*, *Phys. Rev. Lett.* **110**, 263201 (2013)

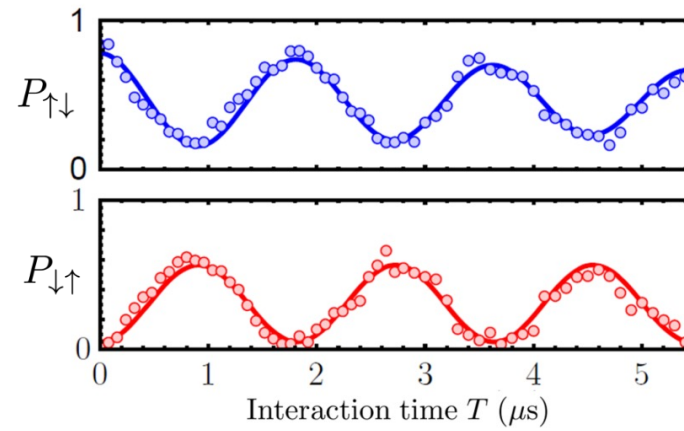


No adjustable parameter!

# Measuring the resonant DDI

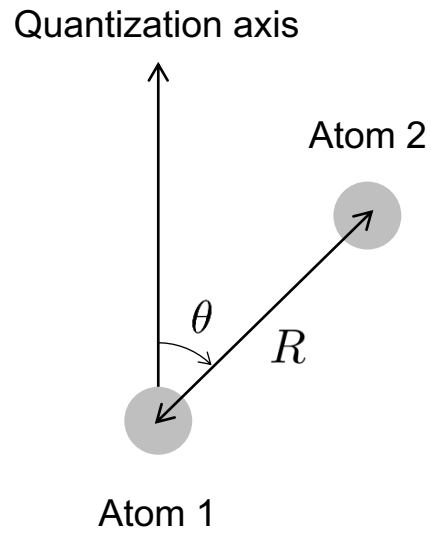


- **Prepare  $|\uparrow\downarrow\rangle$  and let the two atoms evolve**

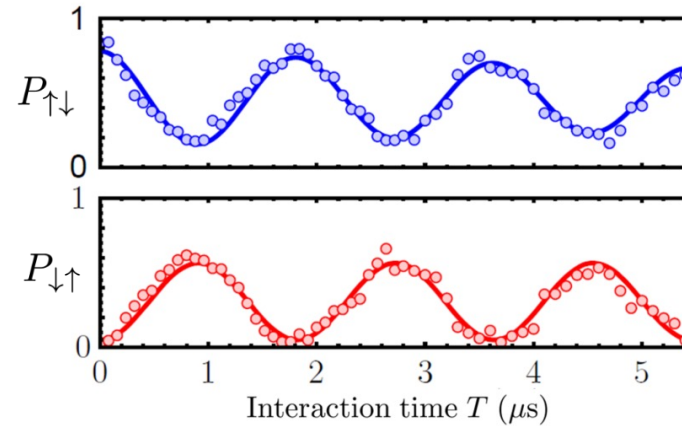


Coherent flip-flops  
over  $R = 30 \mu\text{m}$  !

# Measuring the resonant DDI

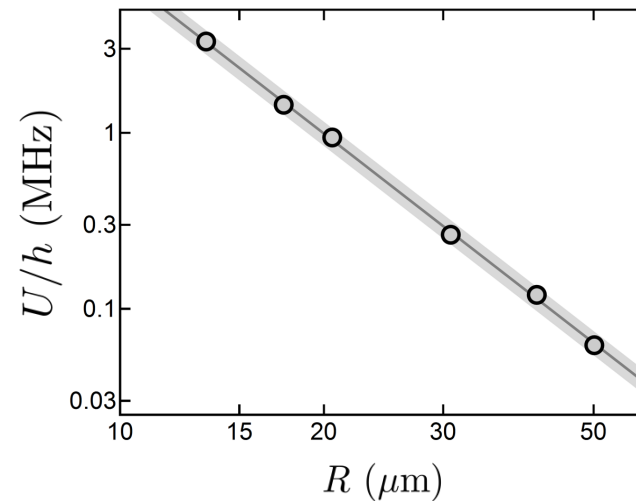


- **Prepare  $|\uparrow\downarrow\rangle$  and let the two atoms evolve**



Coherent flip-flops  
over  $R = 30 \mu\text{m}$  !

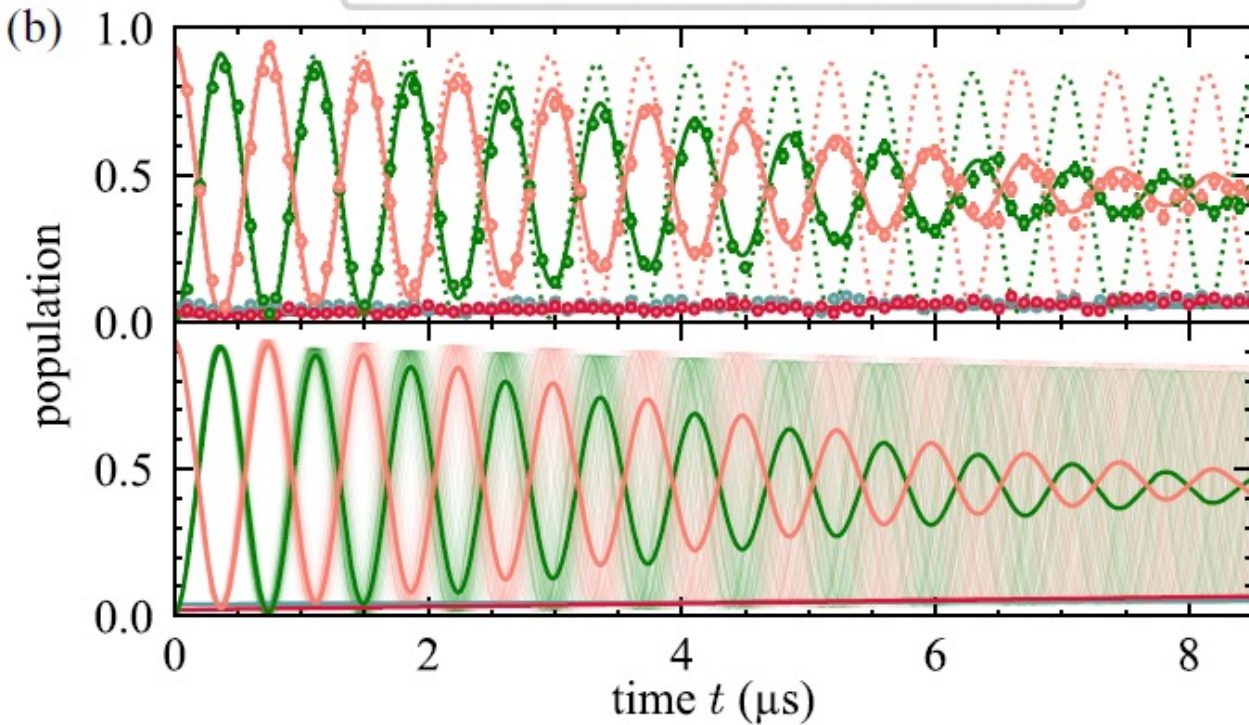
- **Vary the distance**



$1/R^3$  interaction

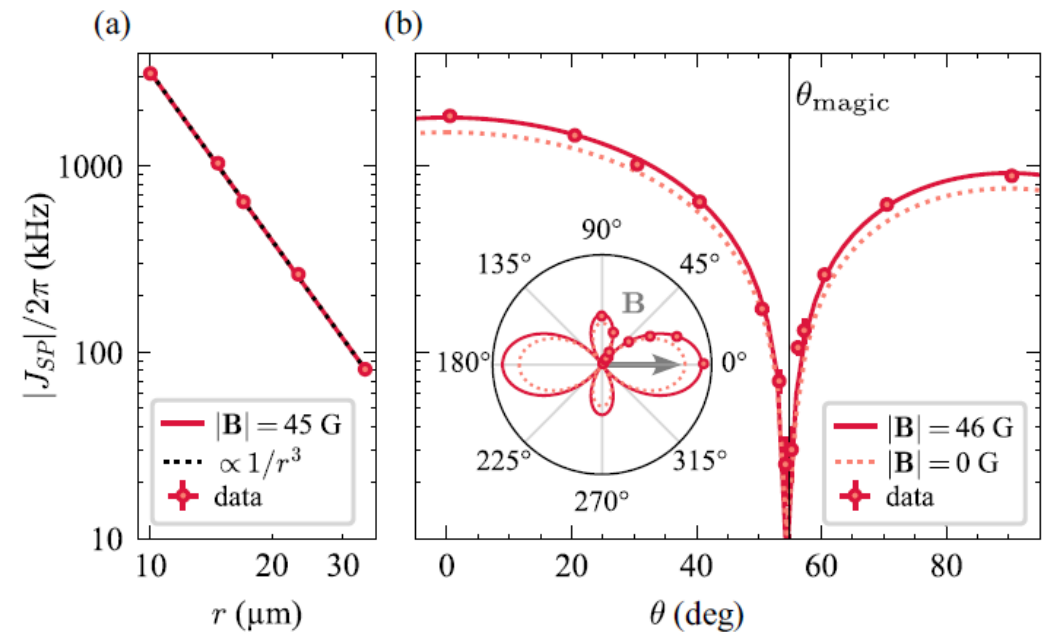
# Measuring the resonant DDI, ten years later

|  $|S, S\rangle$    
 |  $|P, P\rangle$    
 |  $|S, P\rangle$    
 |  $|P, S\rangle$

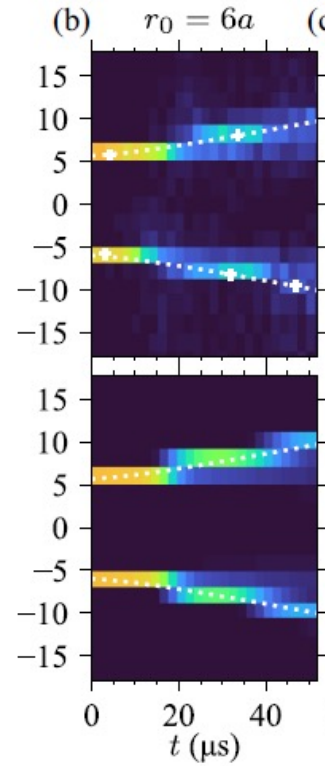
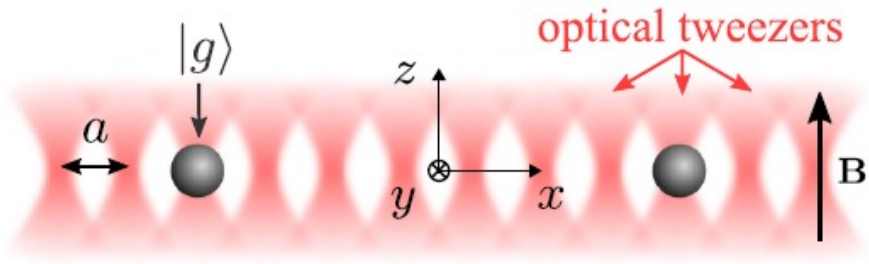


**Angular dependence**

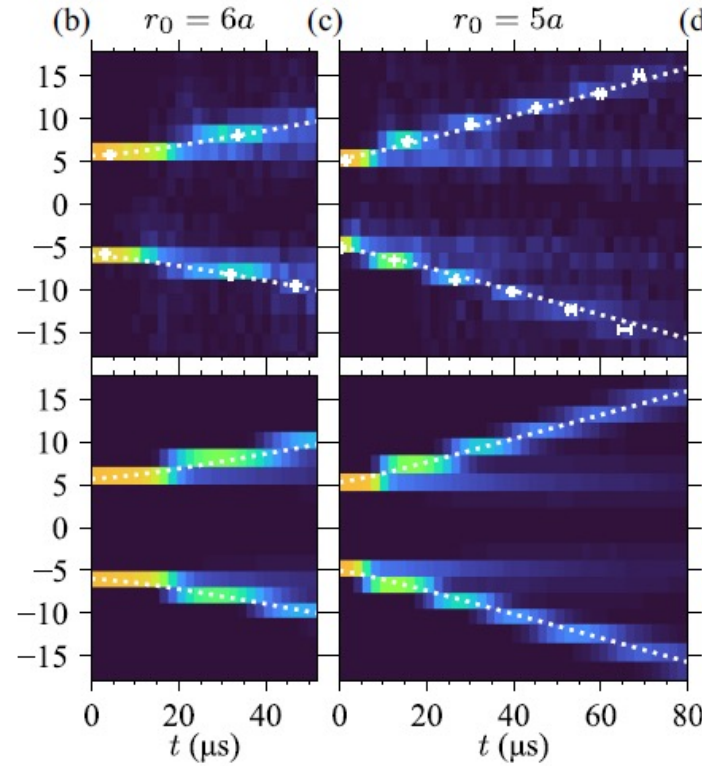
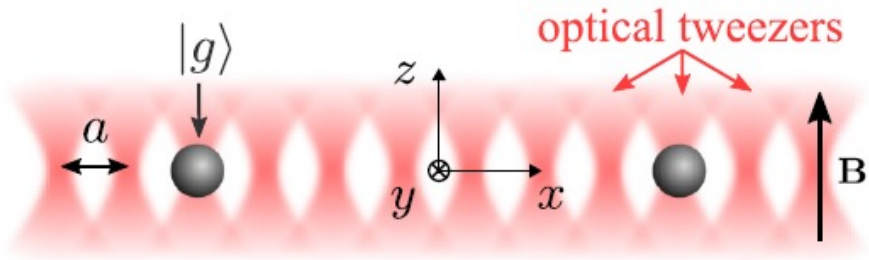
$$V_{\text{dd}} \propto 1 - 3 \cos^2 \theta$$



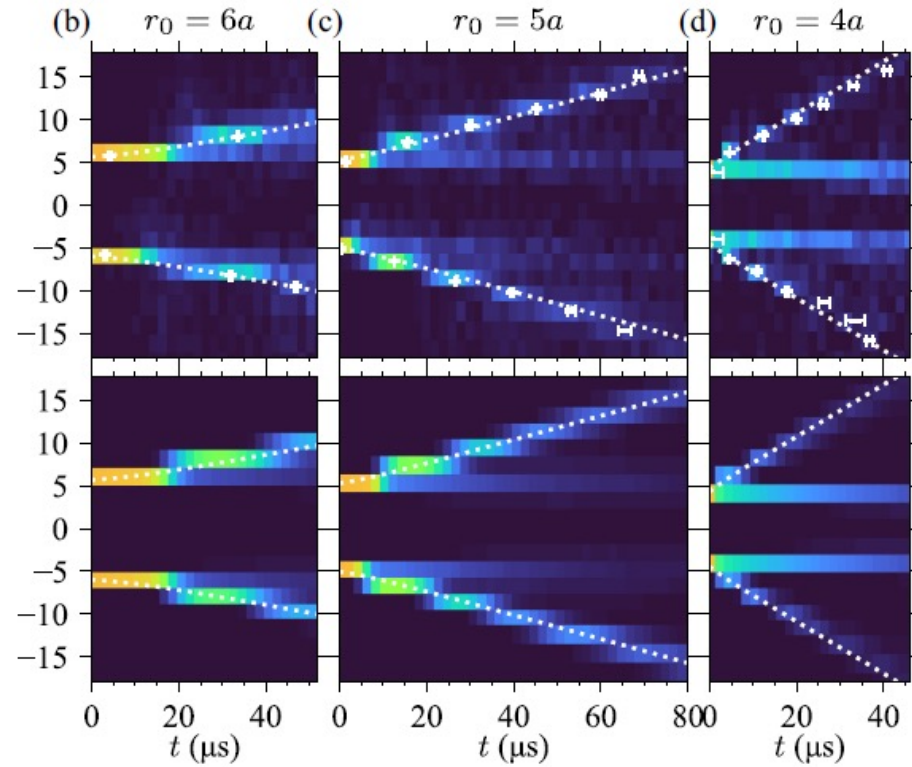
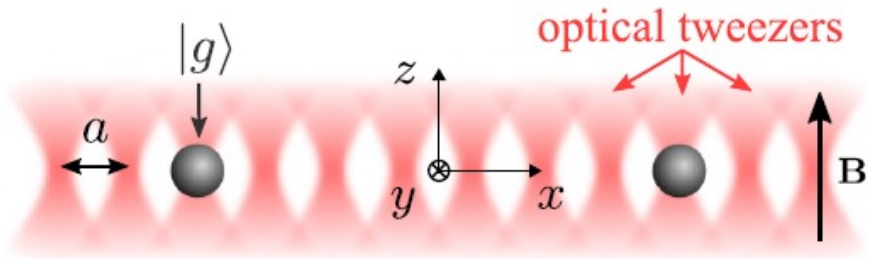
# Playing with the interactions: mechanical effects of the vdW interaction



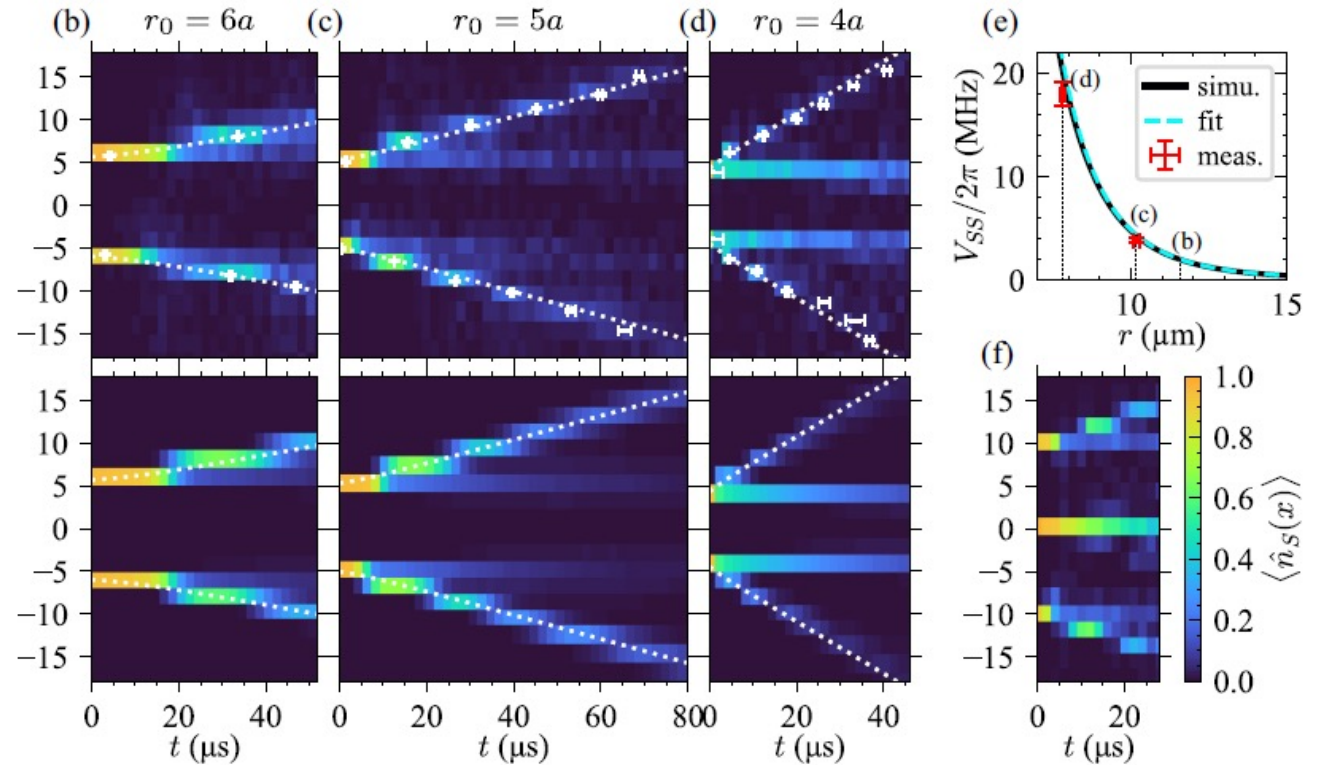
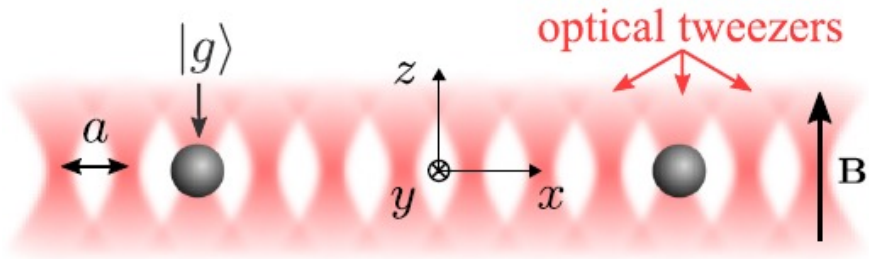
# Playing with the interactions: mechanical effects of the vdW interaction



# Playing with the interactions: mechanical effects of the vdW interaction



# Playing with the interactions: mechanical effects of the vdW interaction



## ***Section 3: Quantum simulation***

***1. Ising model***

***2. Dipolar XY model***

***3. Bosonic  $t - J$  model***

# ***Section 3: Quantum simulation***

***1. Ising model***

*2. Dipolar XY model*

*3. Bosonic  $t - J$  model*

# *The transverse-field Ising model*

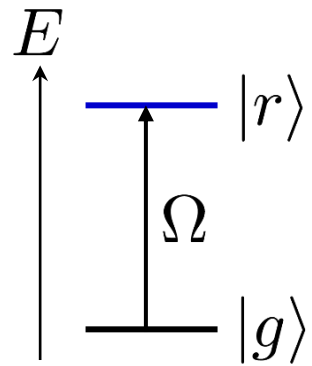
P. Scholl *et al.*, *Nature* **595**, 233 (2021)



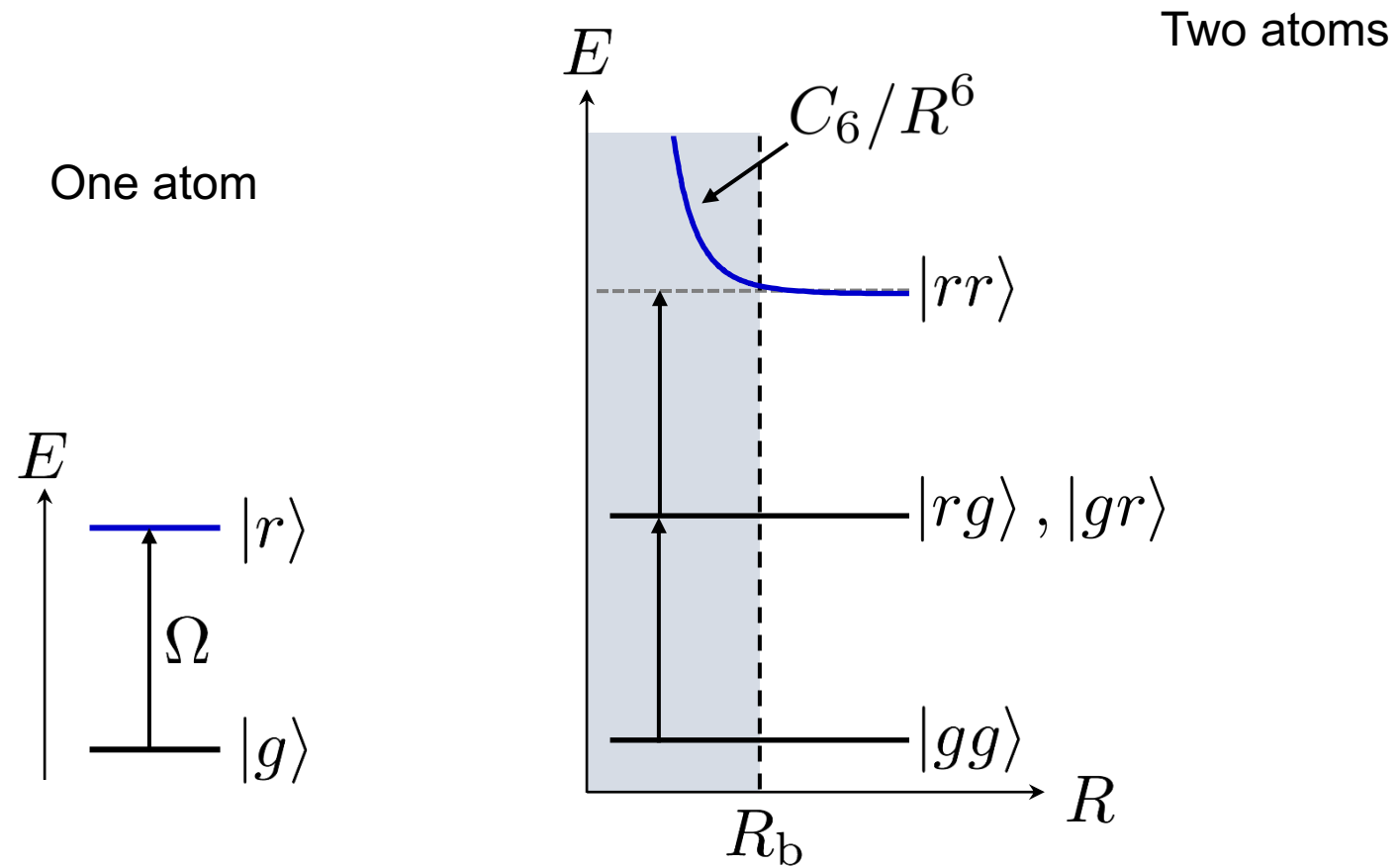
Andreas Läuchli  
(Innsbruck, now at PSI & EPFL)

# Rydberg blockade

One atom

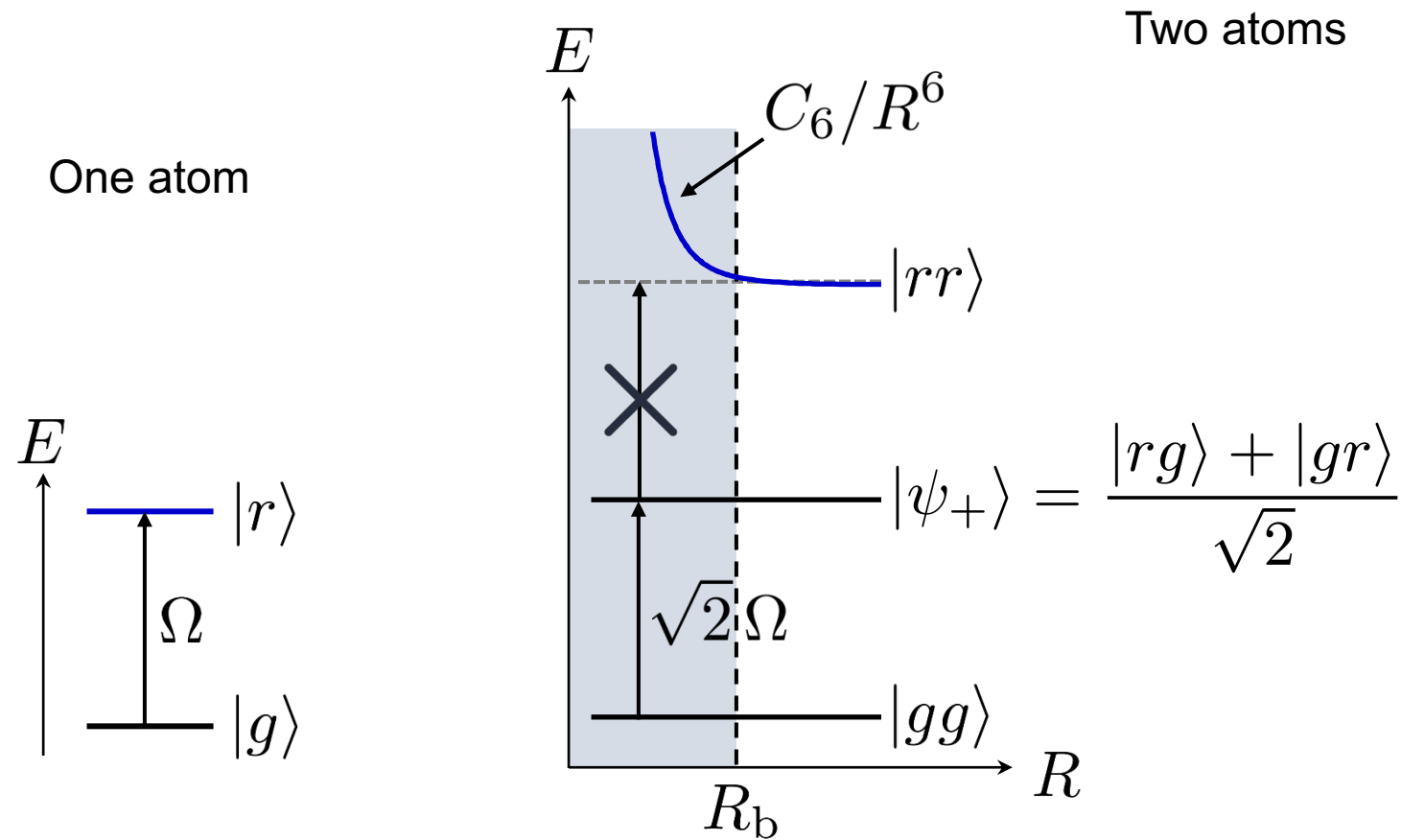


# Rydberg blockade



Blockade radius:  $\hbar\Omega = C_6/R_b^6$

# Rydberg blockade

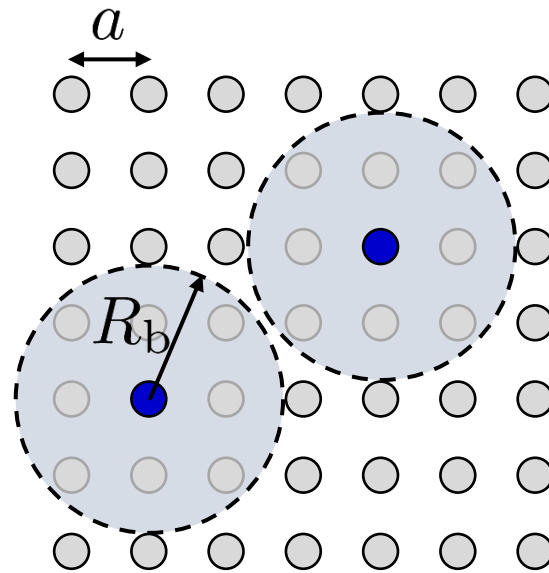


- Generate entanglement
- Basis of two-qubit gates
- Extends to  $N$  atoms in a blockade volume

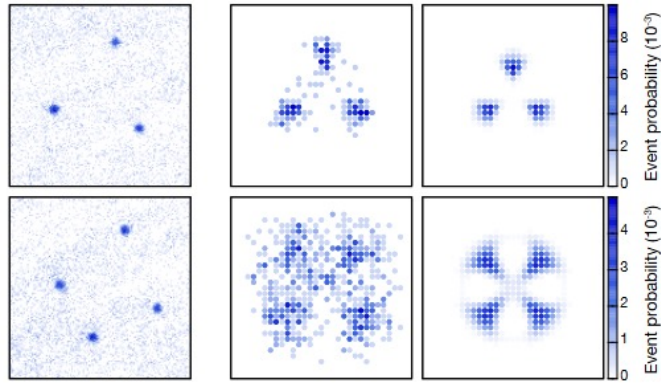
# Rydberg blockade

*Several blockade volumes in the array:*

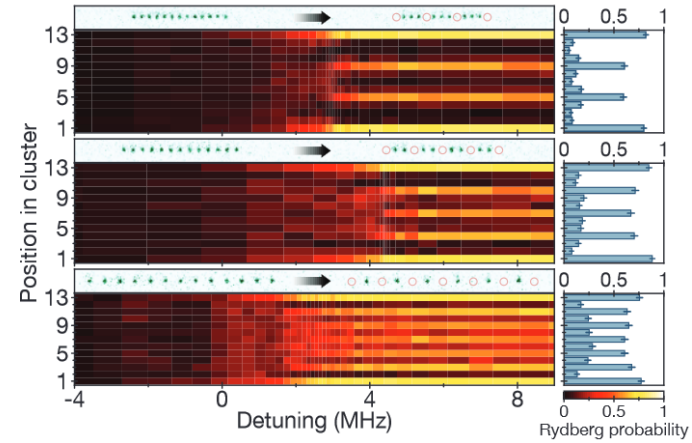
*Strongly correlated quantum many-body systems!*



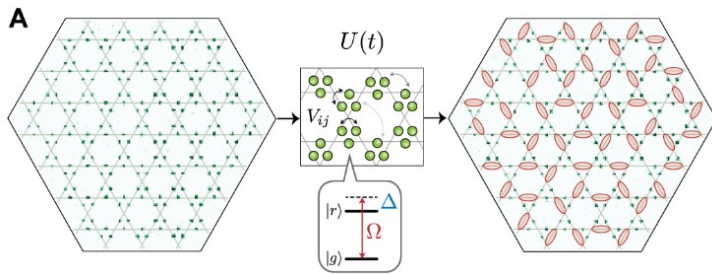
# Many experiments on the Ising model



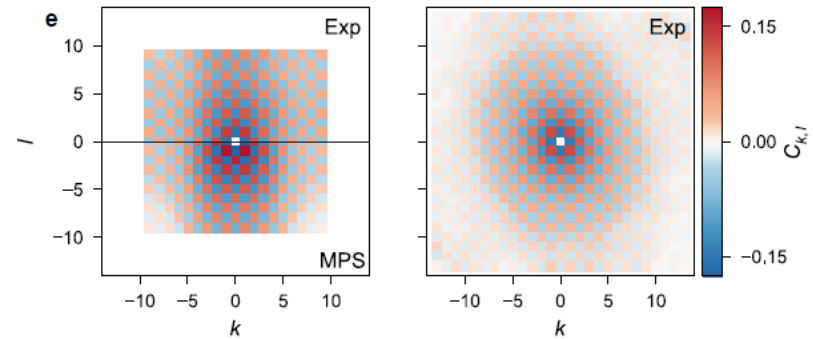
P. Schauss *et al.*, *Nature* **491**, 87 (2012)



H. Bernien *et al.*, *Nature* **551**, 579 (2017)



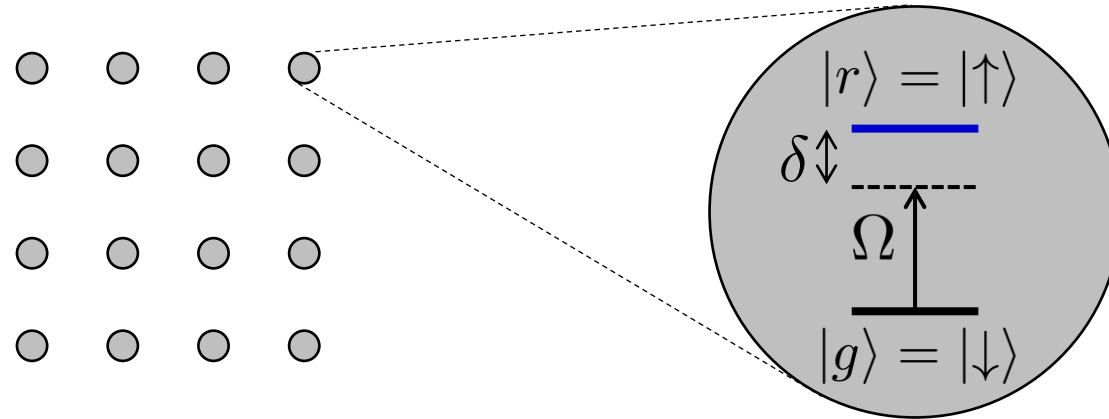
G. Semeghini *et al.*, *Science* **374**, 1242 (2021)



P. Scholl *et al.*, *Nature* **595**, 233 (2021).

**And many, many more examples!**

# Blockade: quantum Ising model



$$n^i = |r_i\rangle \langle r_i|$$

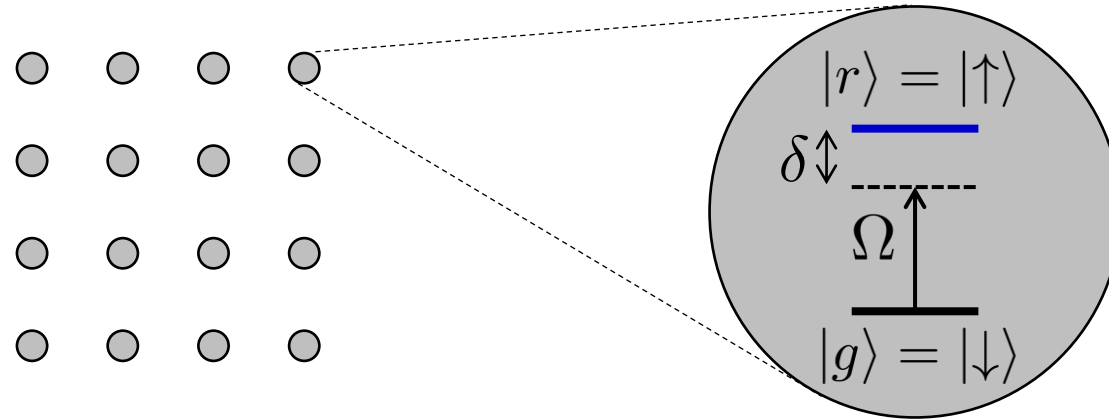
$$H = \sum_i \left( \frac{\hbar\Omega}{2} \sigma_x^i - \hbar\delta n^i \right) + \sum_{i < j} \frac{C_6}{R_{ij}^6} n_i n_j$$

Rabi frequency

Laser detuning

van der Waals interactions

# Blockade: quantum Ising model



$$n^i = |r_i\rangle \langle r_i| = (1 + \sigma_z^i)/2$$

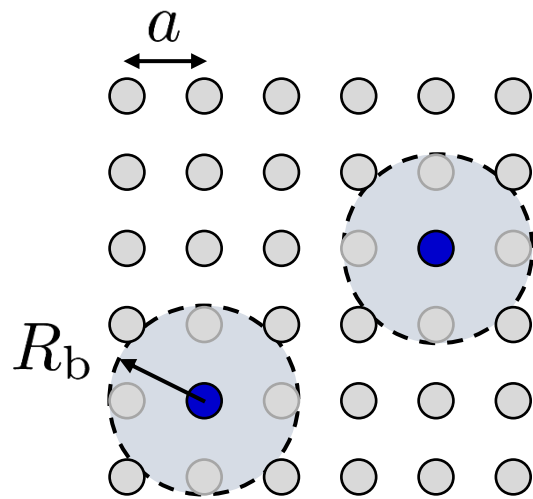
$$H = \sum_i \left( \frac{\hbar\Omega}{2} \sigma_x^i - \hbar\delta n^i \right) + \sum_{i < j} \frac{C_6}{R_{ij}^6} n_i n_j$$

Transverse B    Longitudinal B    Ising couplings

# Ising model: adiabatic preparation

$$R_b = 1.2a$$

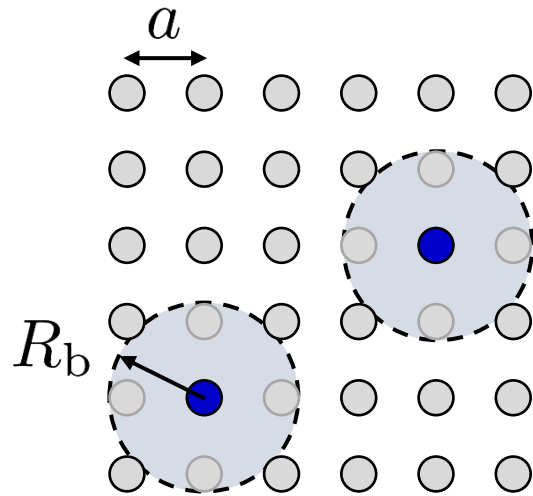
Nearest-neighbor blockade



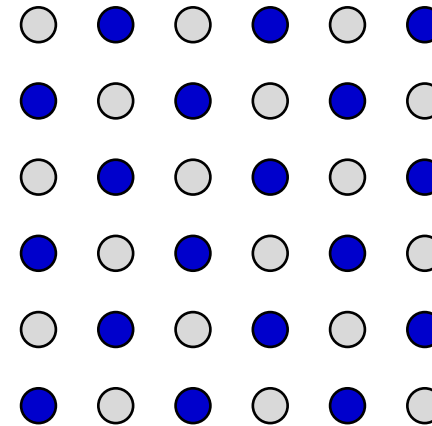
# Ising model: adiabatic preparation

$$R_b = 1.2a$$

Nearest-neighbor blockade



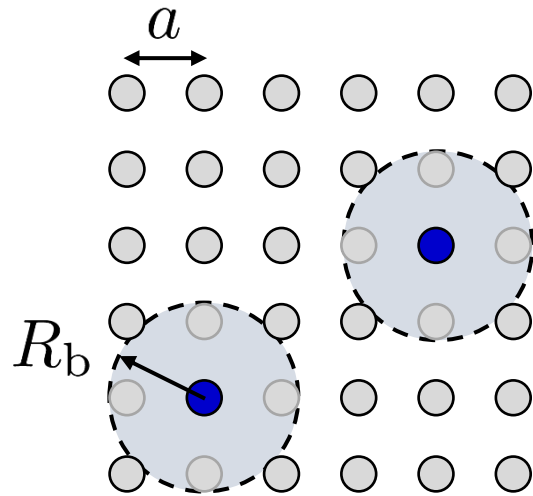
Antiferromagnetic ground state



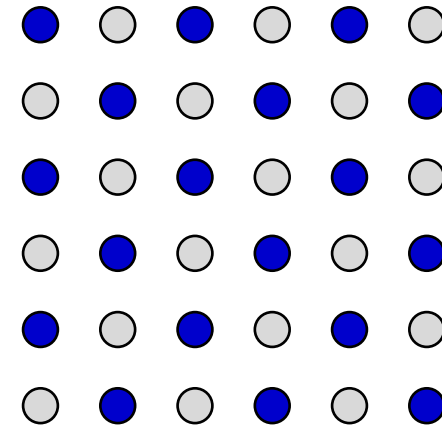
# Ising model: adiabatic preparation

$$R_b = 1.2a$$

Nearest-neighbor blockade

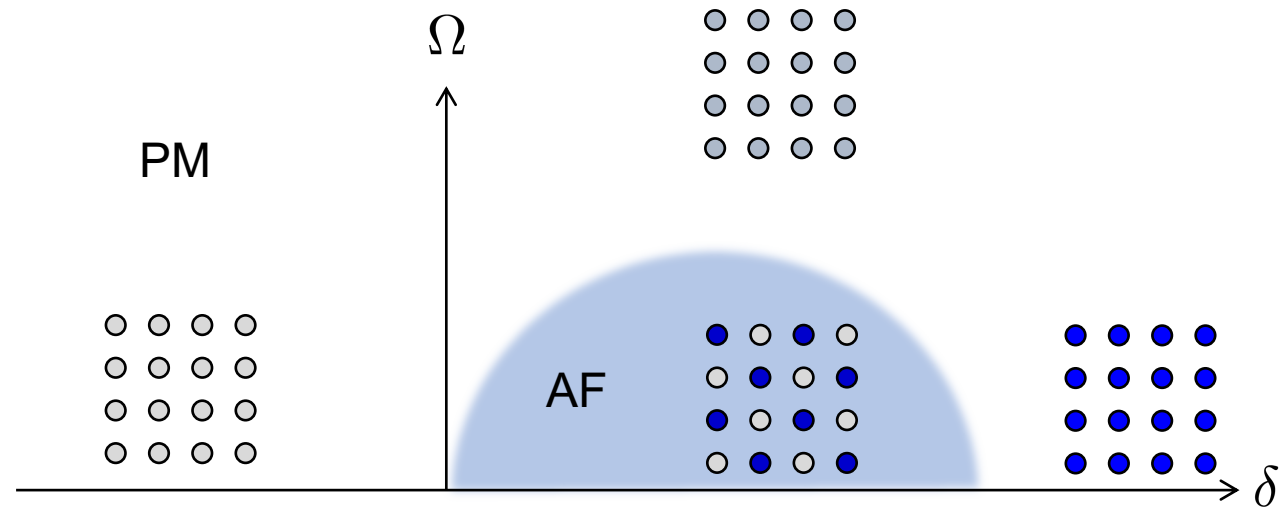


Antiferromagnetic ground state



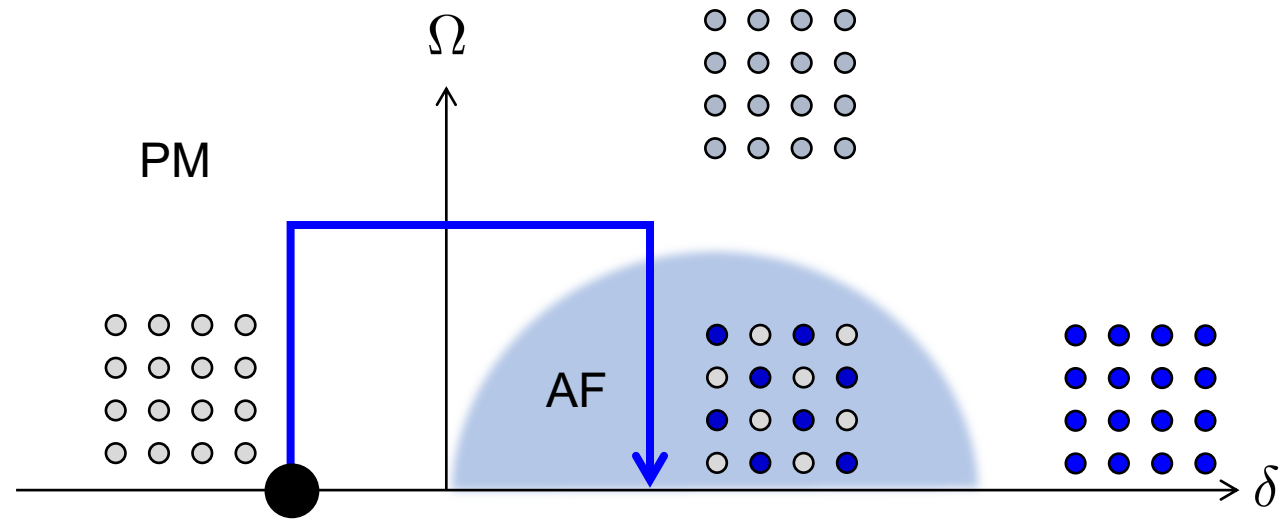
# Ising model: adiabatic preparation

Ising AF phase diagram



# Ising model: adiabatic preparation

## Ising AF phase diagram

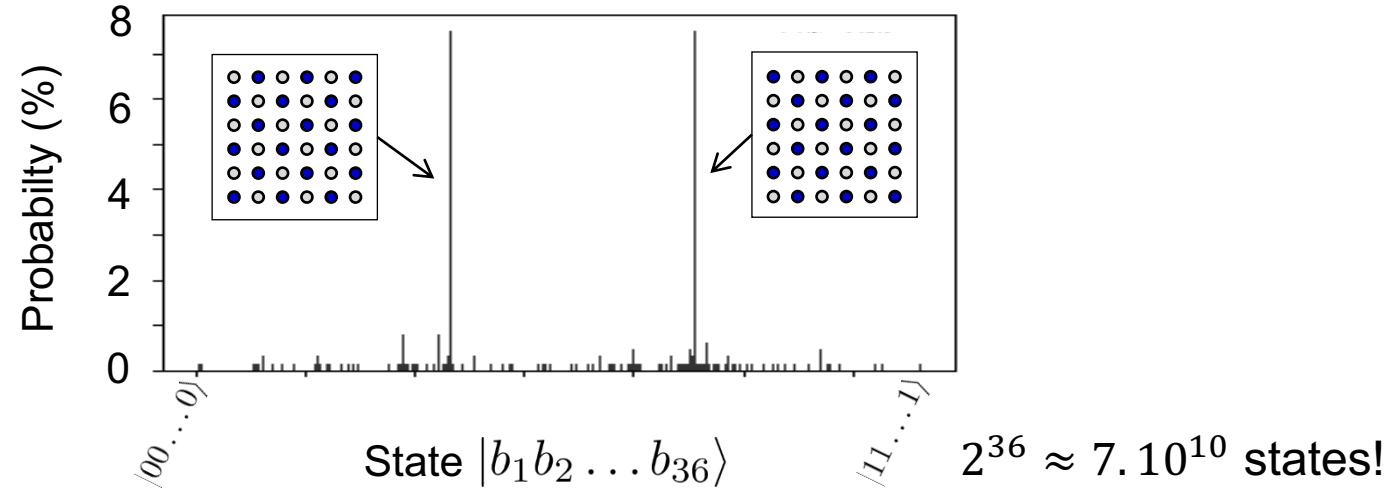
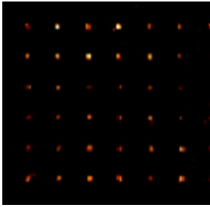


$$H = \sum_i \left( \frac{\hbar\Omega}{2} \sigma_x^i - \hbar\delta n^i \right) + \sum_{i<j} \frac{C_6}{R_{ij}^6} n_i n_j$$

Vary slowly **Rabi frequency** and **detuning** to explore the phase diagram

# 'Adiabatic' preparation on a square array

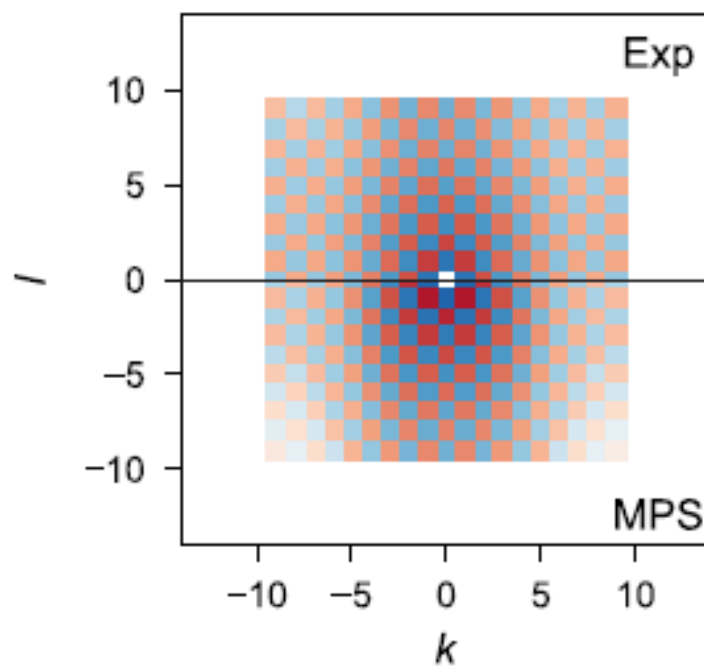
6×6  
square array



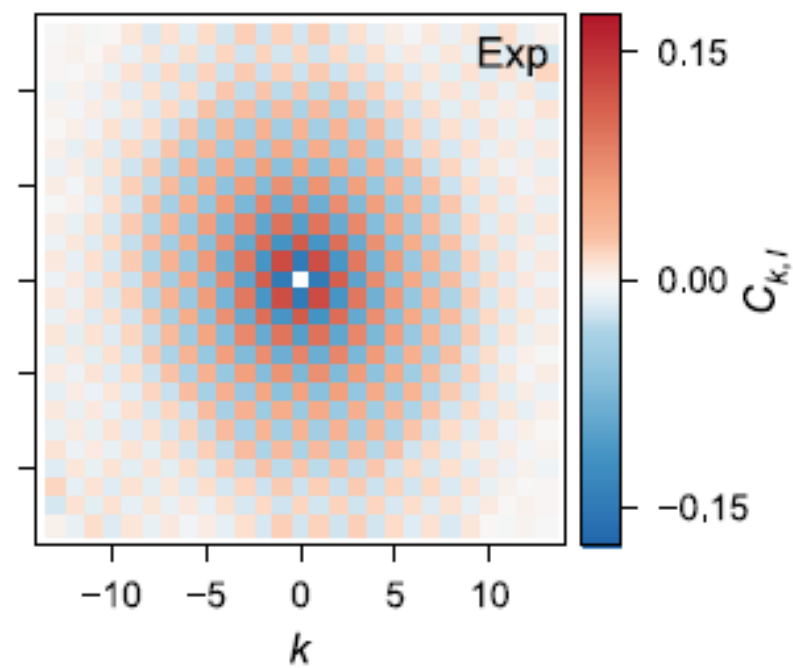
# Correlation functions

$$C_{k,l} = \frac{1}{N_{k,l}} \sum_{i,j} \langle n_i n_j \rangle - \langle n_i \rangle \langle n_j \rangle$$

10×10 array



14×14 array



## **Section 3: Quantum simulation**

*1. Ising model*

**2. Dipolar XY model**

*3. Bosonic  $t - J$  model*

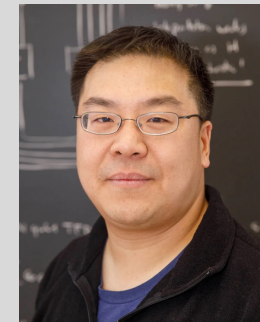
# *The resonant dipole-dipole interaction: dipolar XY model*

C. Chen *et al.*, *Nature* **616**, 691 (2023)

C. Chen *et al.*, *Science* **389**, 483 (2025)

Norm Yao's group (Harvard)

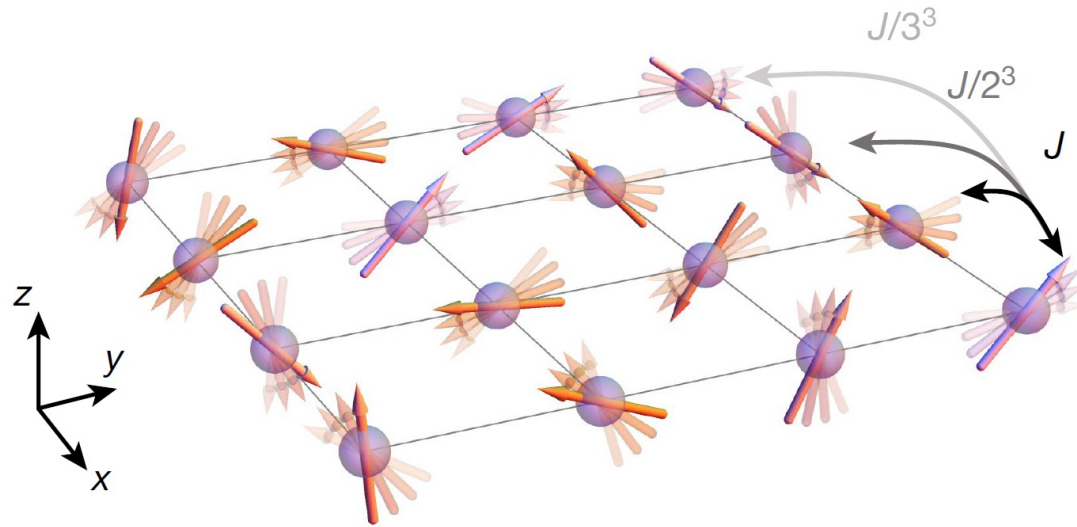
Tommaso Roscilde's group (ENS Lyon)



# *The resonant dipole-dipole interaction: dipolar XY model*



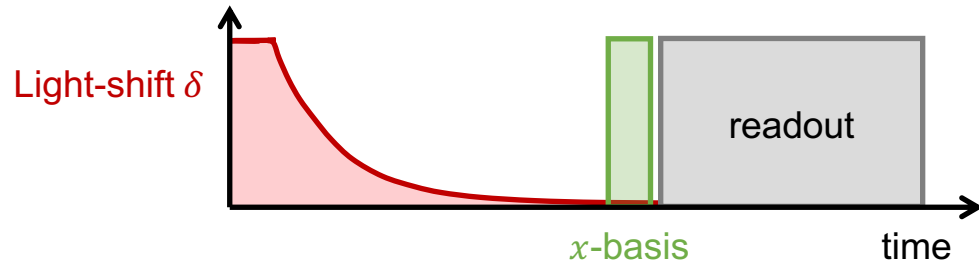
# The resonant dipole-dipole interaction: dipolar XY model



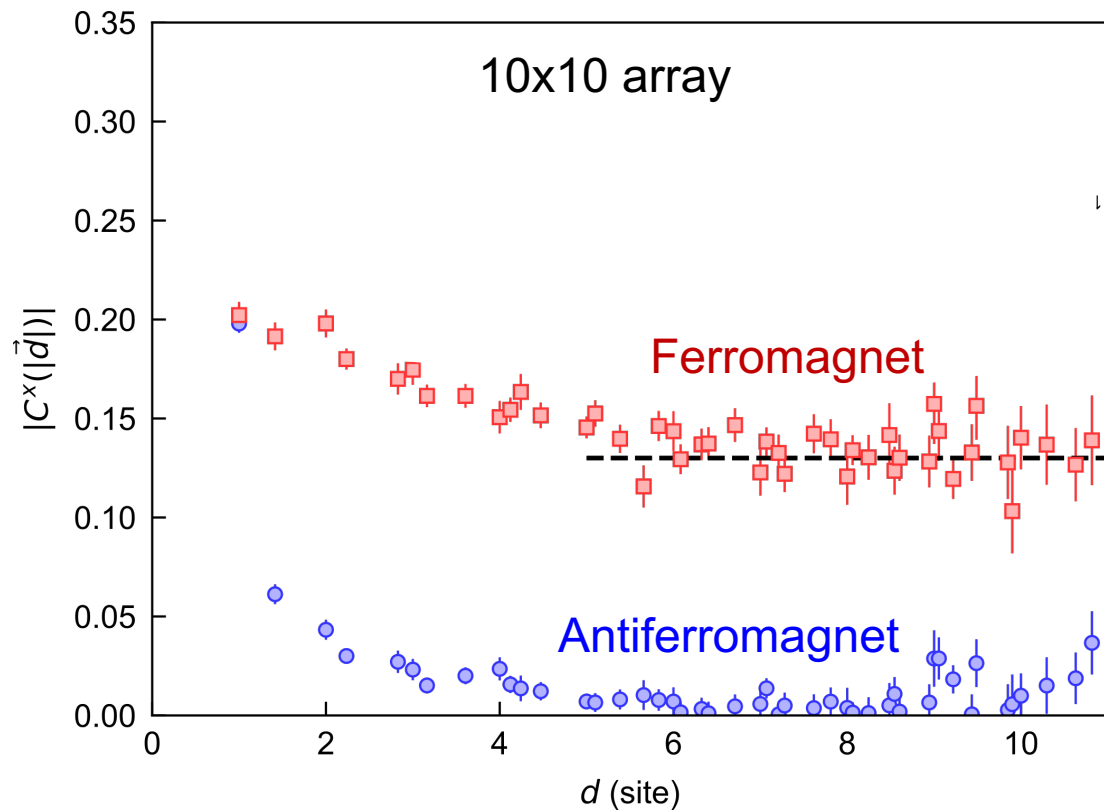
$$H_{XY} = -J \sum_{i < j} \frac{a^3}{r_{ij}^3} (\sigma_i^x \sigma_j^x + \sigma_i^y \sigma_j^y)$$

- **Ground-state properties?**
- **Effects of dimensionality?**
- **Effect of “long-range” couplings?**
- **Elementary excitations?**

# 2d square array: Long-range order for the FM case



Measure the  $xx$  correlations as a function of distance

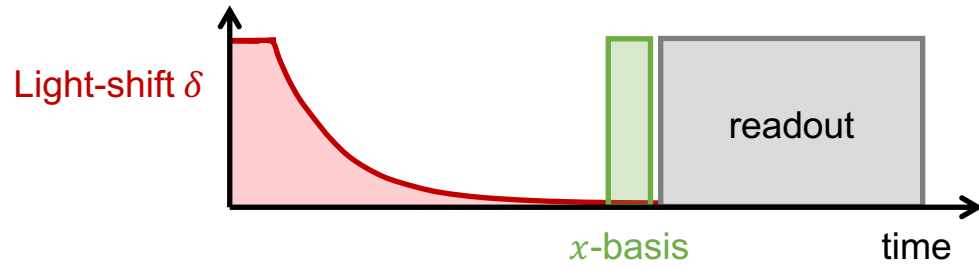


**Ferromagnet:** Long-range order

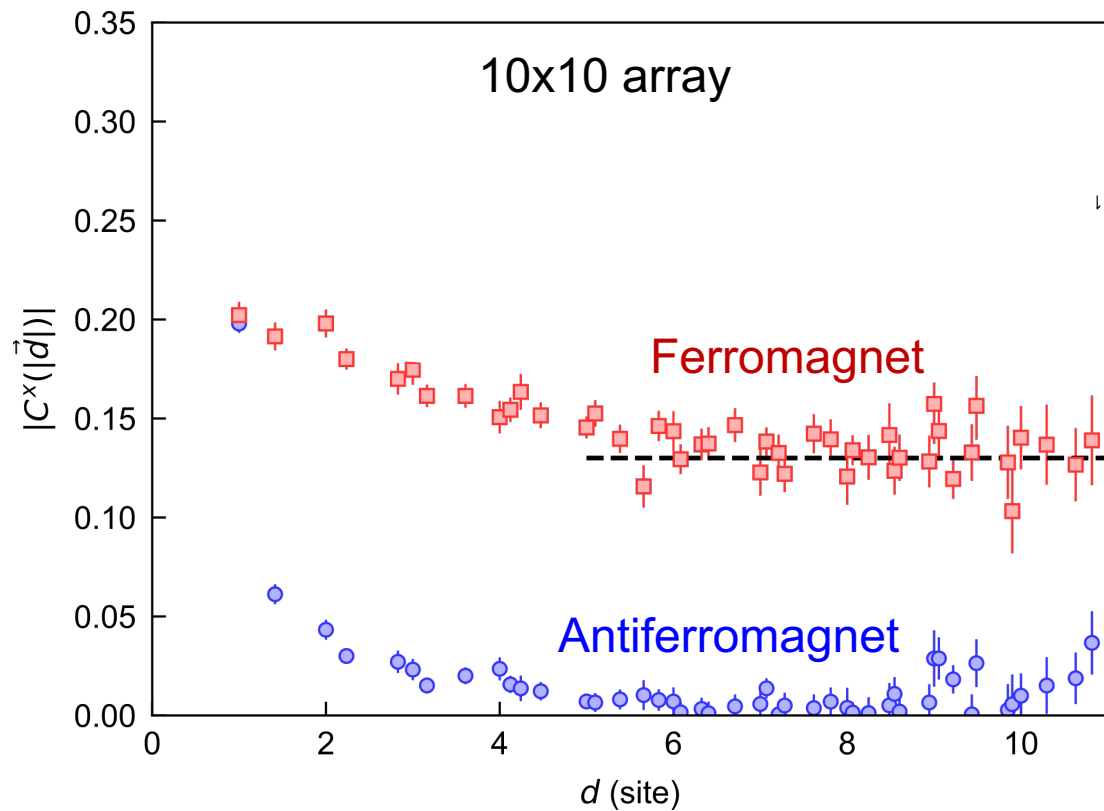
**Antiferromagnet:** Correlations decay to 0

Crucial role of dipolar couplings!

# 2d square array: Long-range order for the FM case



Measure the  $xx$  correlations as a function of distance



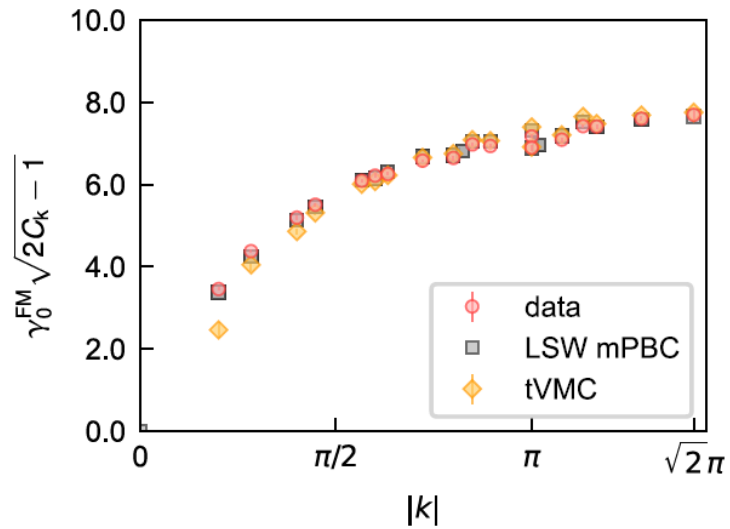
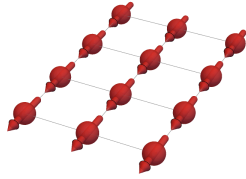
**Ferromagnet:** Long-range order

**Antiferromagnet:** Correlations decay to 0

Crucial role of dipolar couplings!

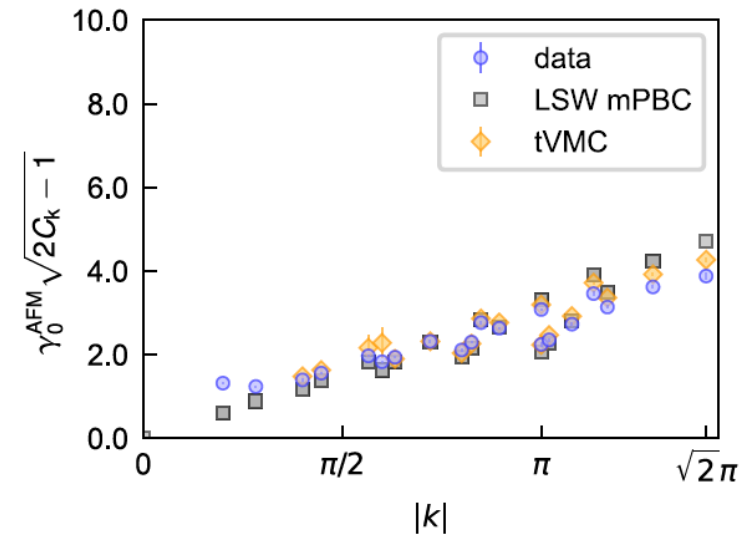
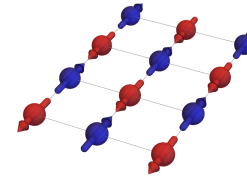
# Dispersion relation of spin waves using quench spectroscopy

Ferromagnet:



$$\omega_k \sim \sqrt{k} \text{ for } k \rightarrow 0$$

Antiferromagnet:



$$\omega_k \sim k \text{ for } k \rightarrow 0$$

**Anomalous dispersion relation of spin waves for the FM dipolar XY model!**

See D. Peter, S. Müller, S. Wessel, and H. P. Büchler, [PRL 109, 025303 \(2012\)](#).

C. Chen *et al.*, [Science 389, 483 \(2025\)](#)

## ***Section 3: Quantum simulation***

*1. Ising model*

*2. Dipolar XY model*

***3. Bosonic  $t - J$  model***

# Doped magnets: bosonic $t - J$ models

M. Qiao *et al.*, *Nature* **644**, 889 (2025)

M. Qiao *et al.*, [2510.17183v1](#)

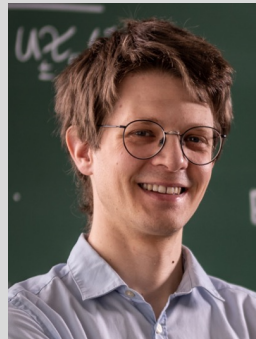
L. Homeier



A. Bohrdt



F. Grusdt



I. Morera



E. Demler



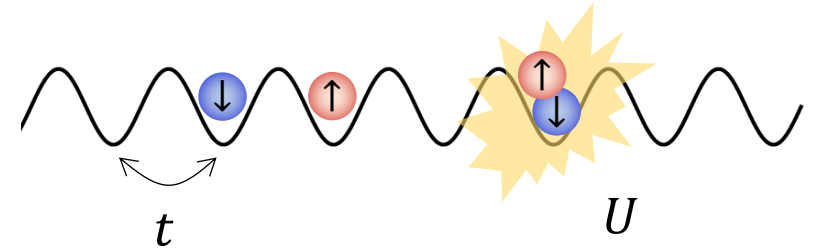
# *Doped magnets: bosonic $t - J$ models*



# Doped magnets: $t - J$ model

**Fermi-Hubbard model in the limit of strong onsite interactions  $U \gg t$ :**

- No double-occupancy: each site either empty, or  $|\uparrow\rangle$ , or  $|\downarrow\rangle$
- Antiferromagnetic couplings  $J \propto t^2/U$  (Heisenberg AFM)
- Away from half-filling, holes can move around



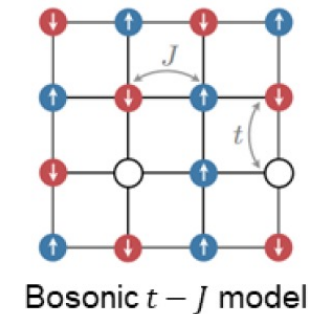
## Interplay between hole tunneling $t$ and spin ordering $J$

Widely tunable ratio  $t/J$

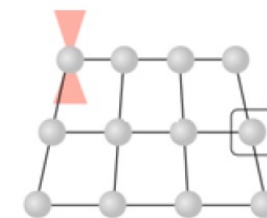
Hole-hole interactions

**Proposal:** three Rydberg levels  $\rightarrow$  bosonic  $t - J - V$  model

L. Homeier *et al.*, [PRL 132, 230401 \(2024\)](#)



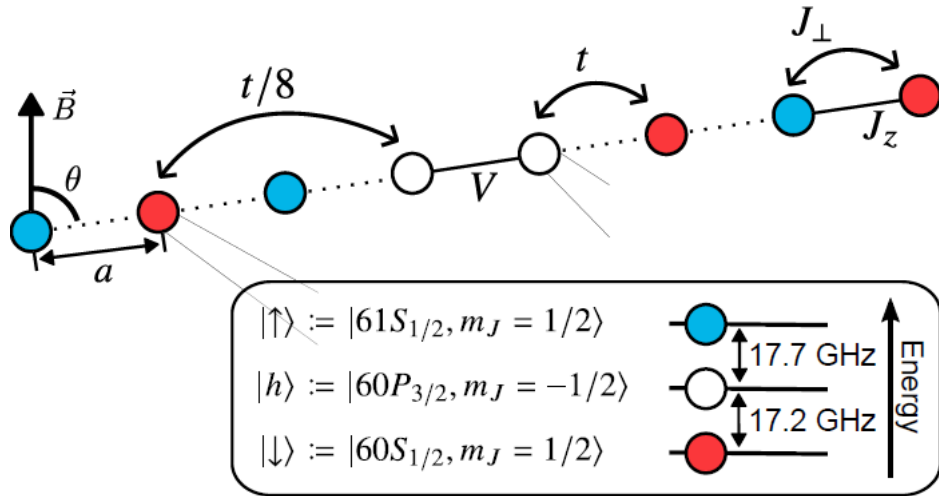
Bosonic  $t - J$  model



Spin mapping

- $\uparrow$  —  $|(n+1)S\rangle$
- $\circ$  —  $|nP\rangle$
- $\downarrow$  —  $|nS\rangle$

# Mapping onto three Rydberg states



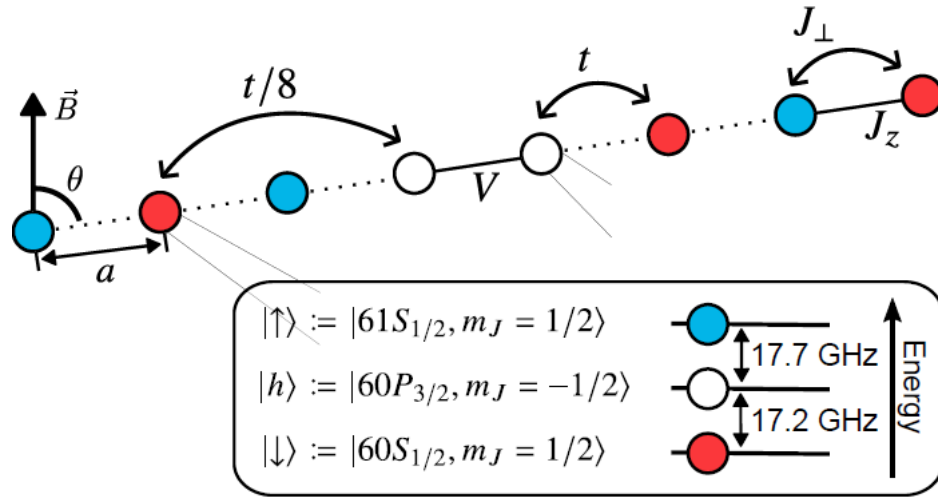
$$\hat{H}_{tJV} = \hat{H}_t + \hat{H}_J + \hat{H}_V,$$

$$\hat{H}_t = - \sum_{i < j} \sum_{\sigma = \downarrow, \uparrow} \frac{t_\sigma}{r_{ij}^3} \left( \hat{a}_{i,\sigma}^\dagger \hat{a}_{j,h}^\dagger \hat{a}_{i,h} \hat{a}_{j,\sigma} + \text{h.c.} \right) \quad \text{Resonant d.d.i. } 60P - 60S \text{ and } 60P - 61S$$

$$\hat{H}_J = \sum_{i < j} \frac{1}{r_{ij}^6} \left[ J^z \hat{S}_i^z \hat{S}_j^z + \frac{J_\perp}{2} \left( \hat{S}_i^+ \hat{S}_j^- + \text{h.c.} \right) \right] \quad \text{van der Waals interactions } 60S / 61S \text{ diag. } (J^z) \text{ and off-diag. } (J_\perp)$$

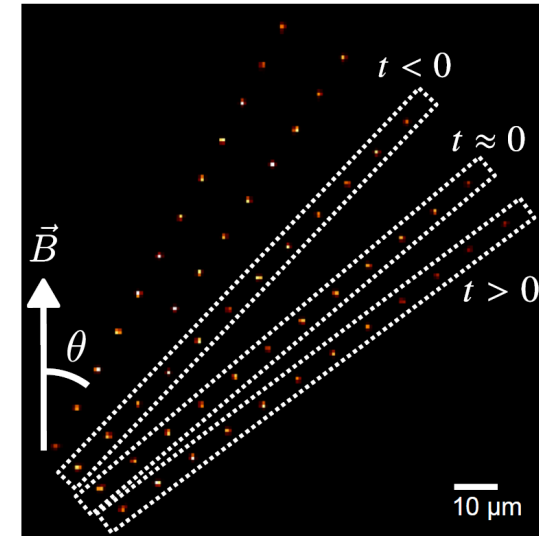
$$\hat{H}_V = \sum_{i < j} \frac{V}{r_{ij}^6} \hat{n}_i^h \hat{n}_j^h. \quad \text{van der Waals interactions } 60P / 60P$$

# Mapping onto three Rydberg states



## Tunability:

Change  $\theta$  to tune tunneling term  $t$



$$\hat{H}_{tJV} = \hat{H}_t + \hat{H}_J + \hat{H}_V,$$

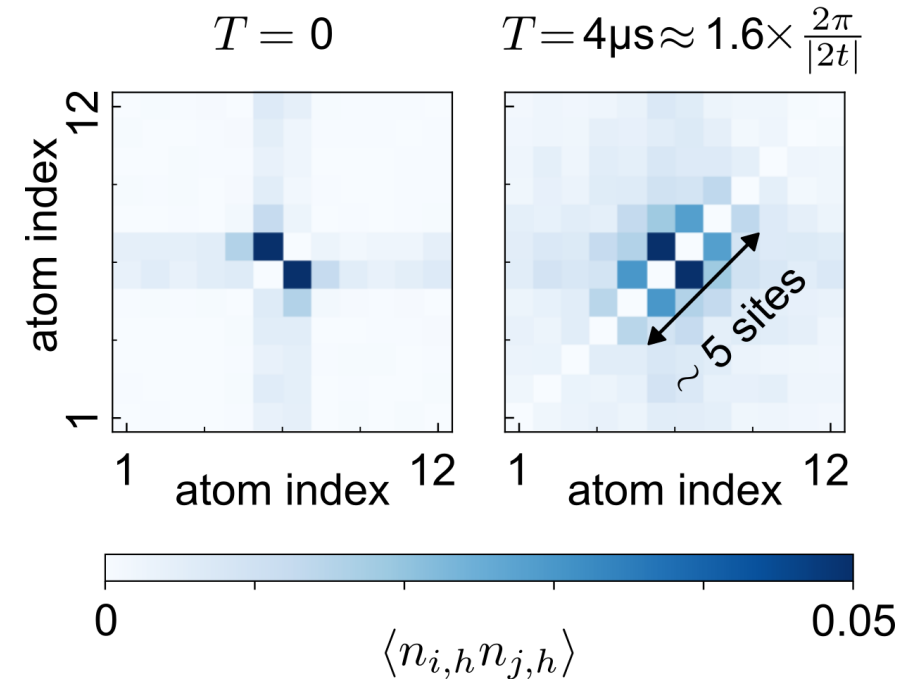
$$\hat{H}_t = - \sum_{i < j} \sum_{\sigma = \downarrow, \uparrow} \frac{t_\sigma}{r_{ij}^3} \left( \hat{a}_{i,\sigma}^\dagger \hat{a}_{j,h}^\dagger \hat{a}_{i,h} \hat{a}_{j,\sigma} + \text{h.c.} \right) \quad \text{Resonant d.d.i. } 60P - 60S \text{ and } 60P - 61S$$

$$\hat{H}_J = \sum_{i < j} \frac{1}{r_{ij}^6} \left[ J^z \hat{S}_i^z \hat{S}_j^z + \frac{J_\perp}{2} \left( \hat{S}_i^+ \hat{S}_j^- + \text{h.c.} \right) \right] \quad \text{van der Waals interactions } 60S / 61S \text{ diag. } (J^z) \text{ and off-diag. } (J_\perp)$$

$$\hat{H}_V = \sum_{i < j} \frac{V}{r_{ij}^6} \hat{n}_i^h \hat{n}_j^h. \quad \text{van der Waals interactions } 60P / 60P$$

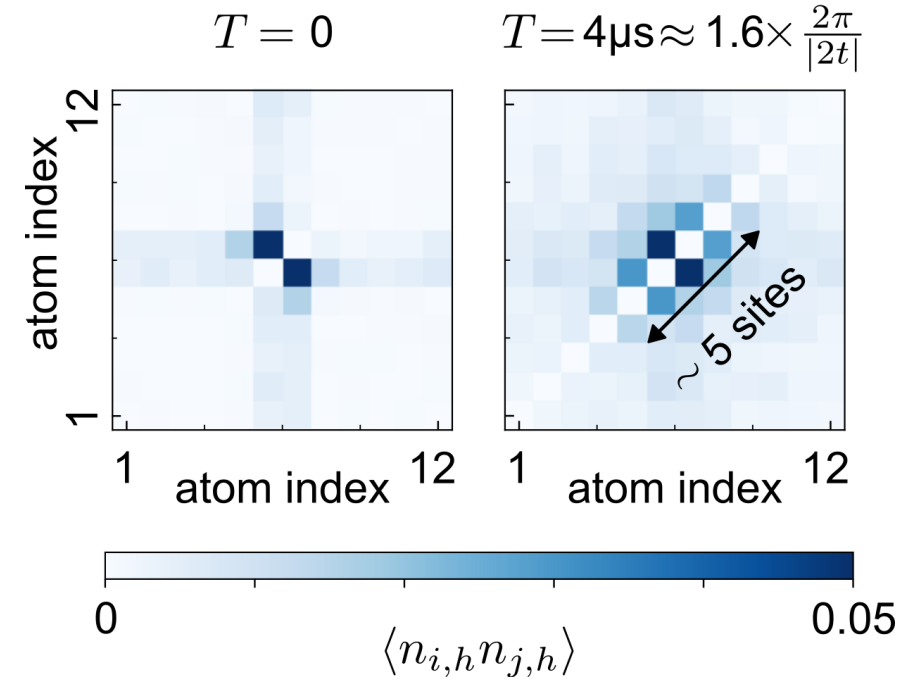
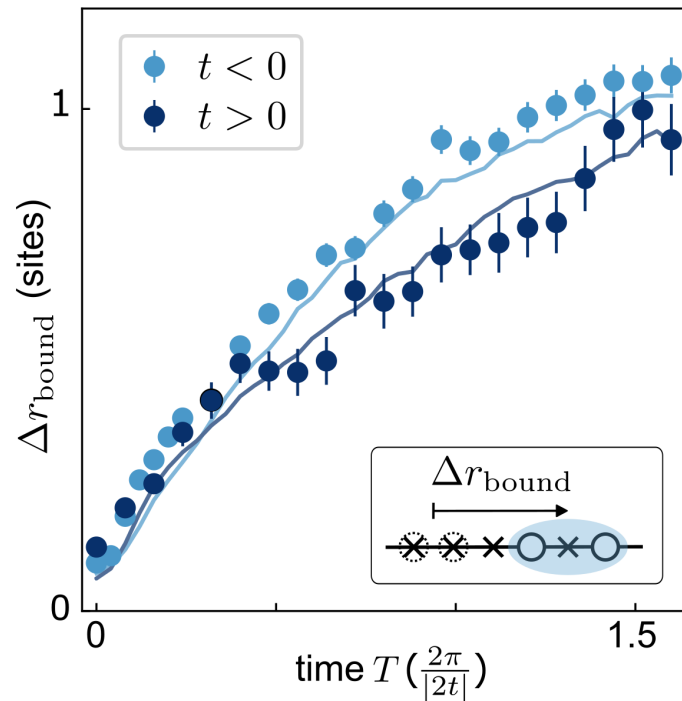
# Hole-hole bound states in a 12-site chain

Correlated motion of two holes:



# Hole-hole bound states in a 12-site chain

Correlated motion of two holes:



Effective tunneling rate of the hole pair

$$t_{\text{eff}} = \frac{t^2}{V - J_z/4} - \frac{t}{8}$$

***Thanks for your attention!***