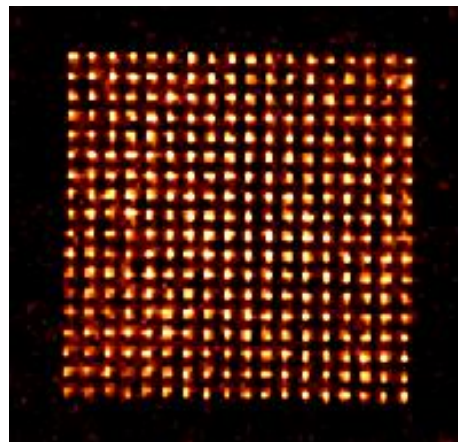


Quantum simulation with Rydberg atom arrays

Thierry Lahaye

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

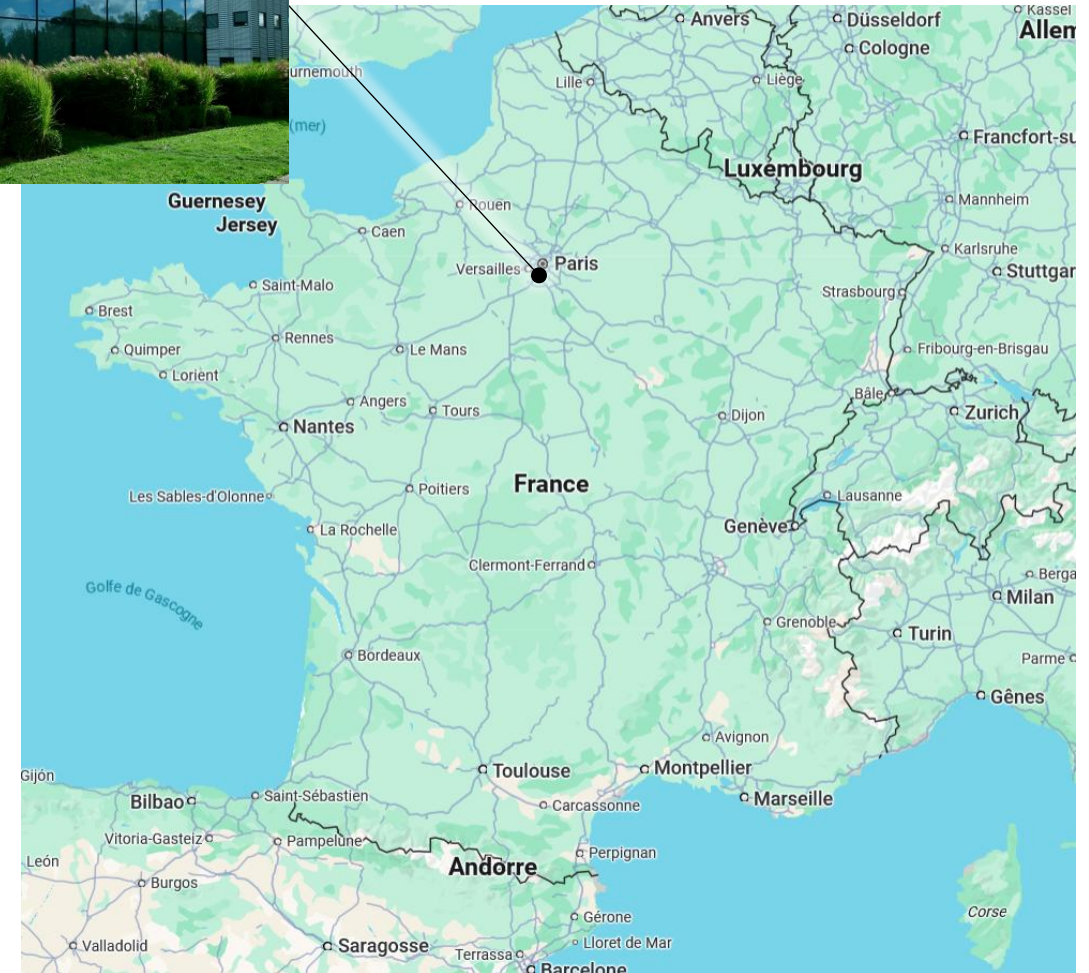


Winter School on Ultracold Quantum Many-Body Systems

Benasque, Feb. 1-7, 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

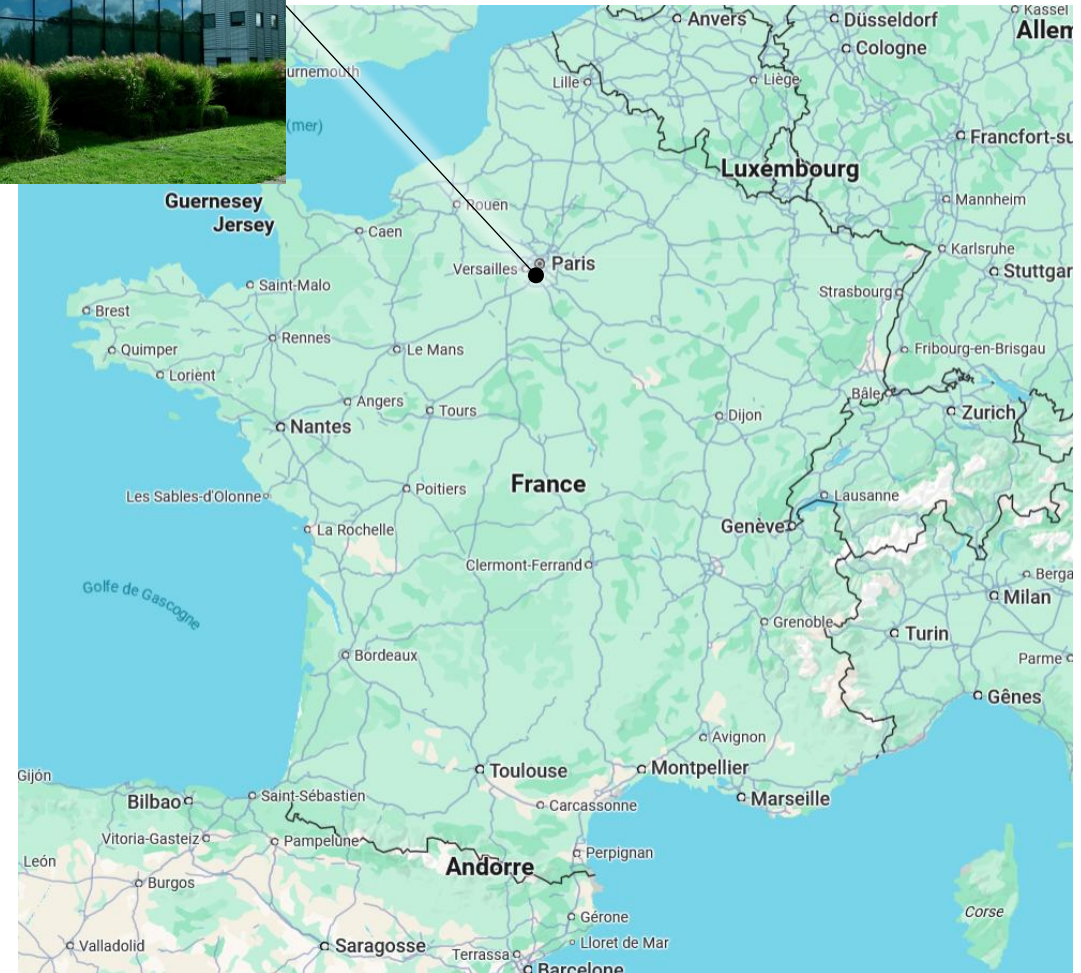
- A CNRS researcher



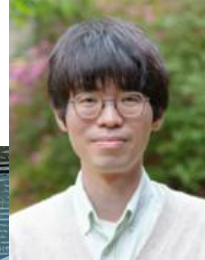
- I work at *Institut d'Optique* in Palaiseau (~20 km south of Paris)



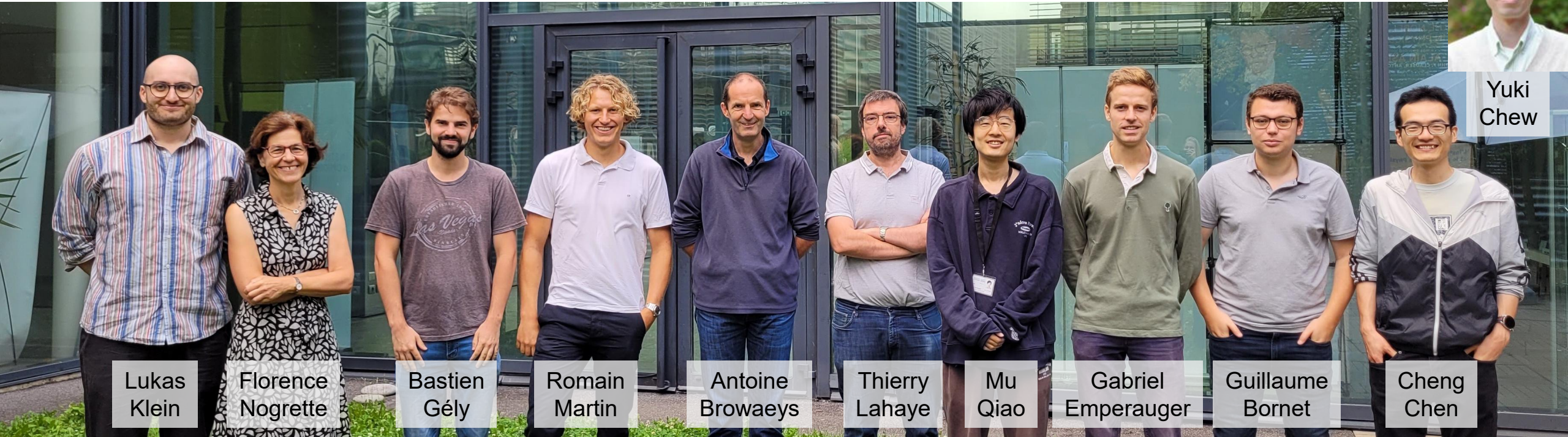
- I'm also a co-founder and scientific advisor at Pasqal



The Rydberg team in Palaiseau



Yuki
Chew



Lukas
Klein

Florence
Nogrette

Bastien
Gély

Romain
Martin

Antoine
Browaeys

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...

- **Remain at very introductory level**
- **Emphasis on experimental aspects**

Before starting...

- **Remain at very introductory level**
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- **Mix of slides and blackboard**

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**

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

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

LECTURE 1

Monday, February 2nd, 2026

Lecture 1

1. Intro: quantum simulation of spin models

2. Single atoms in optical tweezers

3. Defect-free arrays

4. A few recent developments

Quantum many-body physics

“Elementary” quantum physics: single-particle

Condensed-matter physics & statistical physics:

- $N \gg 1$ interacting particles
- Quantum statistics (fermions, bosons)

And yet, very often, a description in terms of almost independent particles “works well”

Quantum many-body physics

“Elementary” quantum physics: single-particle

Condensed-matter physics & statistical physics:

- $N \gg 1$ interacting particles
- Quantum statistics (fermions, bosons)

And yet, very often, a description in terms of almost independent particles “works well”

For instance: metal or insulator? Band theory



Fermi liquid theory (Landau) : almost independent “quasi-particles”

Quantum many-body physics

But does not always work: “Strongly-correlated systems”

Mott insulators (e.g. NiO)

Should be a **conductor** according to band theory, but is an **insulator**

Effect arises from Coulombic repulsion between the electrons



N.F. Mott

Quantum many-body physics

But does not always work: “Strongly-correlated systems”

Mott insulators (e.g. NiO)

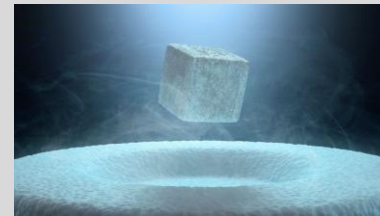
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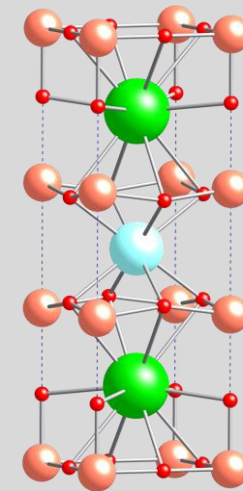
N.F. Mott

High- T_c superconductors



SC even at 77K (liquid N_2)

Not described by BCS



Quantum many-body physics

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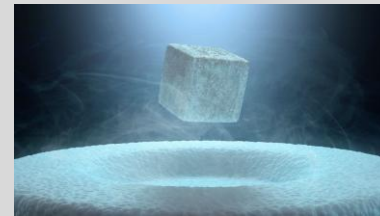
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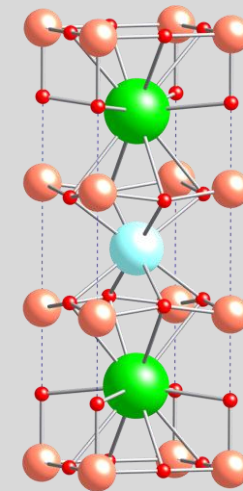
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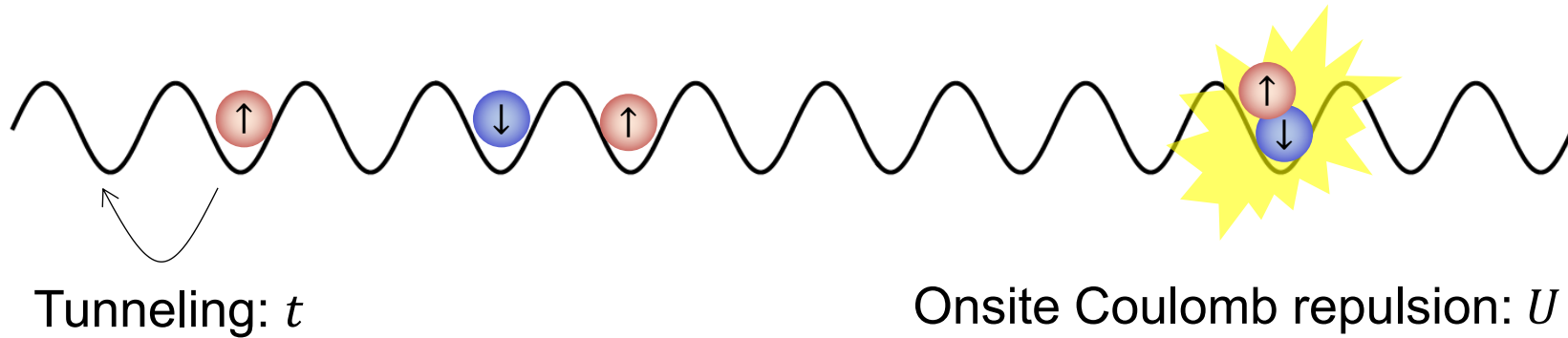
Minimalistic model: Hubbard Hamiltonian (1963)

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

Even simplistic models can't be solved...

Minimalistic model: 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?

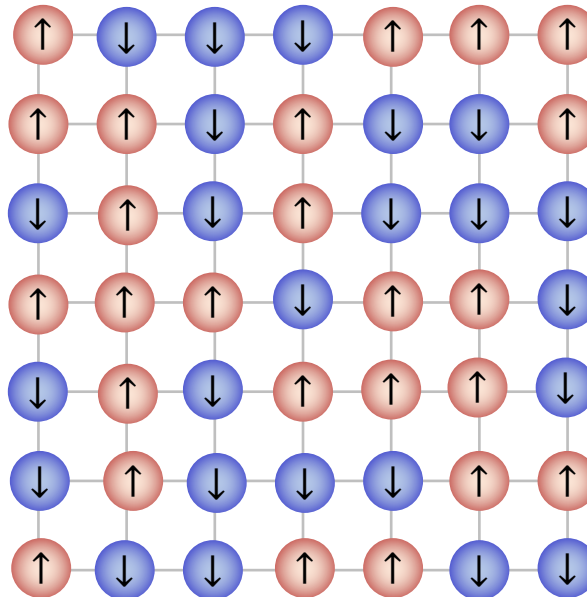
Quantum magnetism

Let's simplify further the "simplistic" model!

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

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

Mott insulator phase

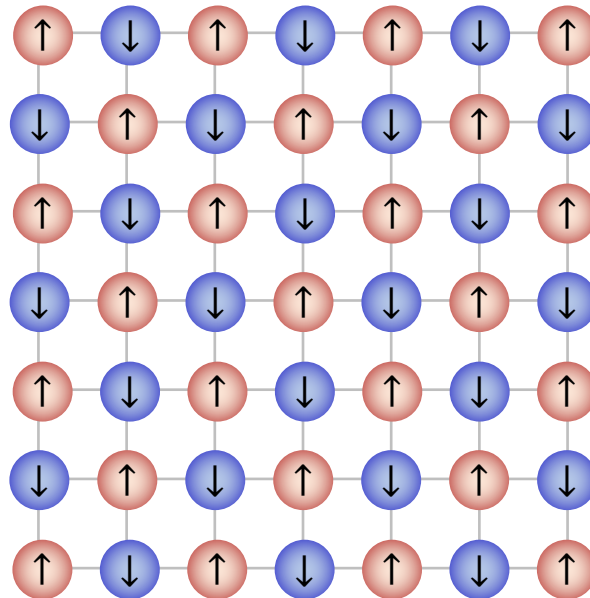


Is it the end of the story?

Quantum magnetism

Not quite! Antiferromagnetic ordering

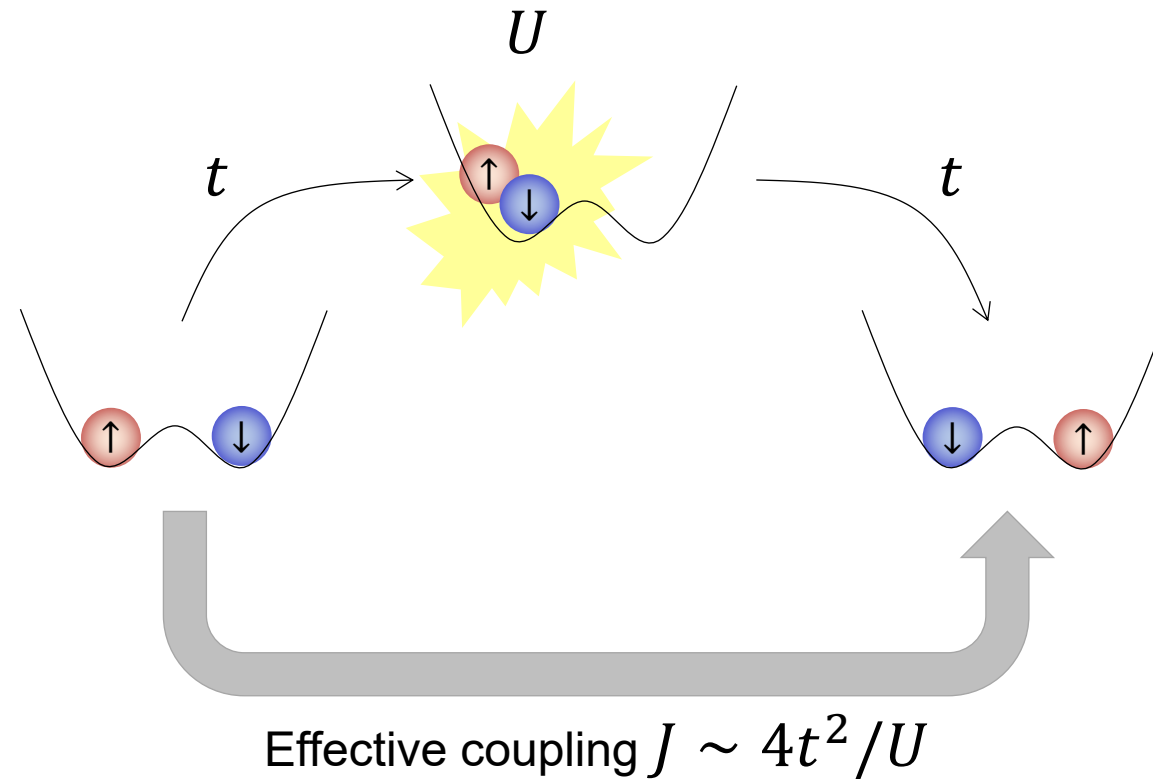
The system can lower its energy by ordering the spins



Quantum magnetism

The system can lower its energy by ordering the spins

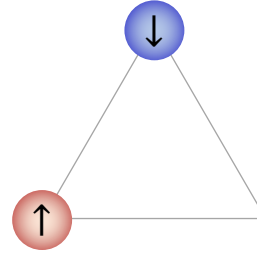
“Virtual” tunneling couples the states $|\uparrow\downarrow\rangle$ et $|\downarrow\uparrow\rangle$, which lowers the energy



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

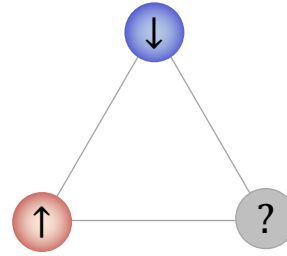
Still many open questions in quantum magnetism

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



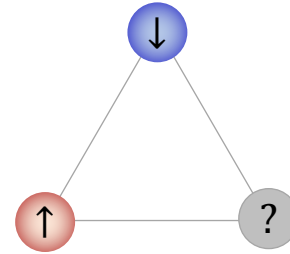
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Still many open questions in quantum magnetism

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

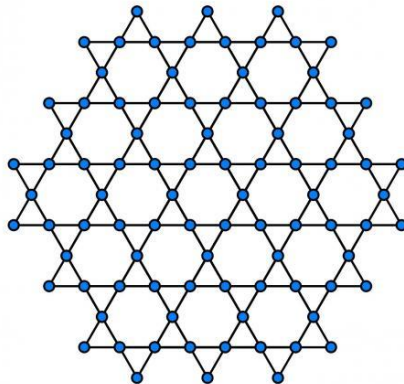


Heisenberg

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

+

Kagome lattice



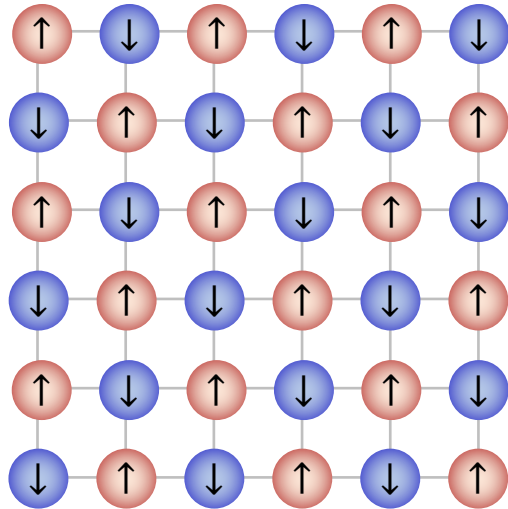
“Spin liquids”

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



Limits of exact numerical simulations

Brute-force approach for N spins $\frac{1}{2}$: diagonalize a $2^N \times 2^N$ matrix!



$2^{36} \simeq 68$ billion states!

Several weeks of calculations on supercomputers



Of course, stunning recent progress in numerical methods (tensor networks, machine learning, etc.)

Feynman 1982

International Journal of Theoretical Physics, Vol. 21, Nos. 6/7, 1982

Simulating Physics with Computers

Richard P. Feynman

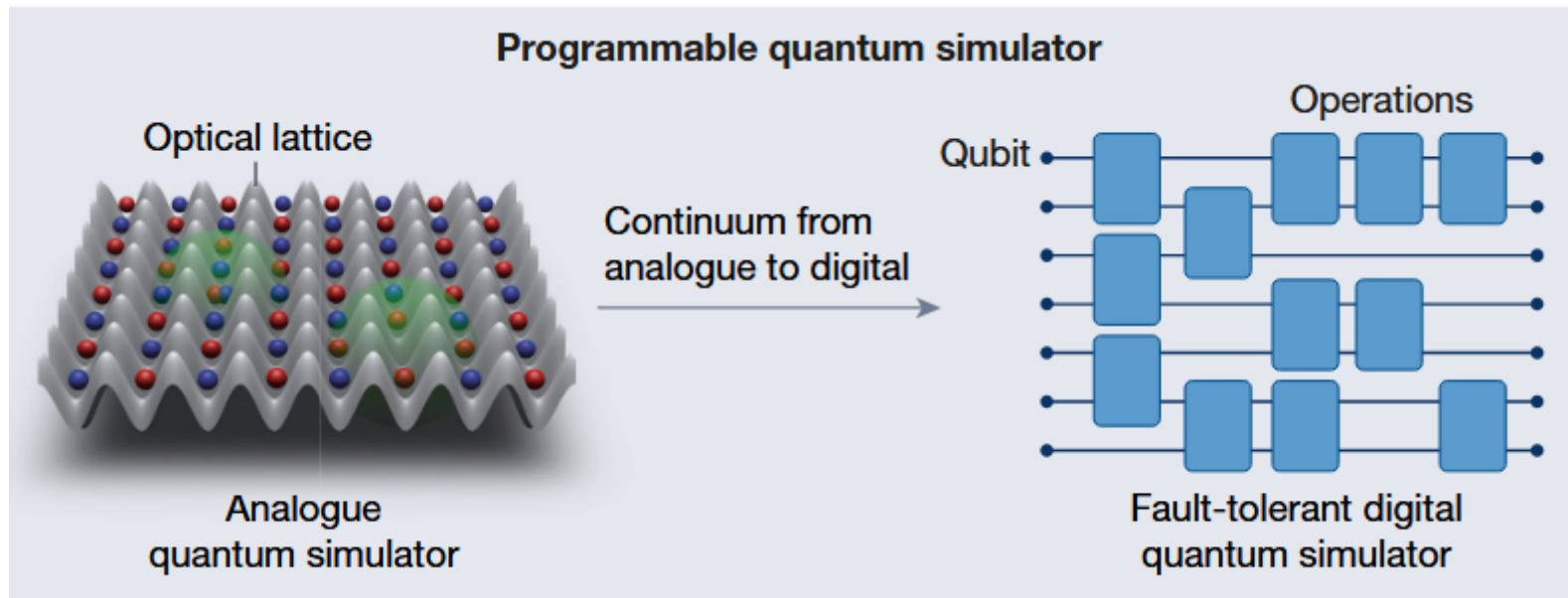
Department of Physics, California Institute of Technology, Pasadena, California 91107

Received May 7, 1981



If you want to make a simulation of nature, you'd better make it quantum mechanical.

Universal quantum computers for digital qu. sim.

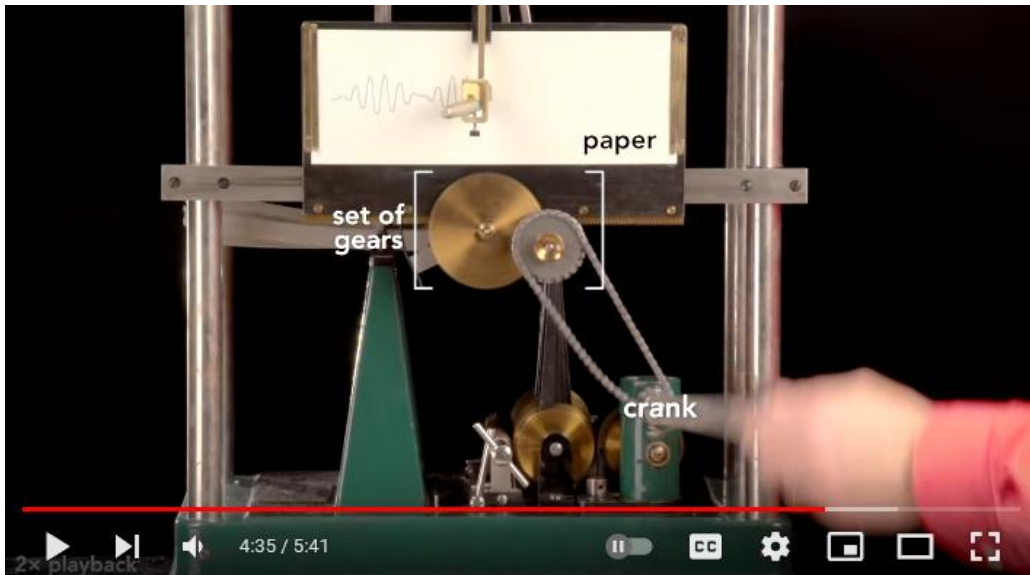


A. Daley *et al.*, *Nature* **602**, 667 (2022)

Even for relatively small systems, requires FTQC with
~ hundreds of logical qubits
~ millions of gates...

Analog computers have a long history...

- Astronomical clocks, end of Middle Ages:



- Albert Michelson's "*Harmonic Analyzer*"
<https://www.youtube.com/watch?v=GyYflzRVu6M>

Analog quantum simulators: the orthodox view

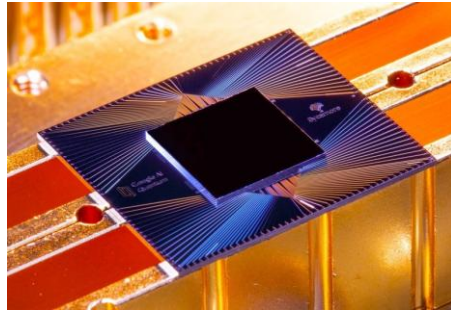
- Use a quantum system governed by the same equations as the system of interest
- More control than in “natural” systems
(geometry, number of atoms, site-resolved measurements, dynamics...)
- Direct answer to relevant questions by experiments
- Problem of the validation of the results.

*My (slightly) unorthodox view: Analog quantum **stimulators***

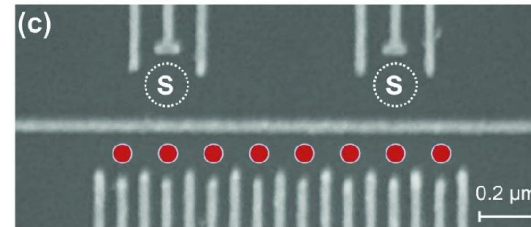
- Use a quantum system governed by **almost** the same equations as the system of interest
- **Different controls** compared with “natural” systems
(geometry, number of atoms, site-resolved measurements, dynamics...)
- Direct answer to relevant questions by experiments, but also (and above all) **stimulates** new questions
- Problem of the validation of the results... **Like in any experiment** or calculation in physics!

Many platforms

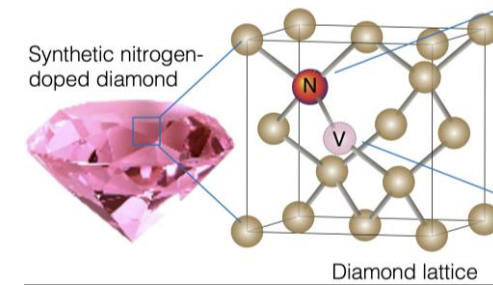
Superconducting qubits



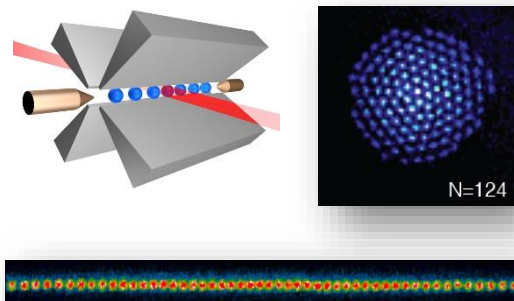
Electron quantum dots



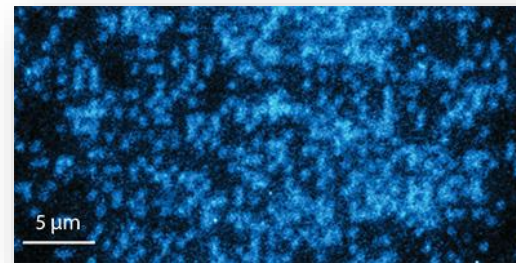
Defects in solids



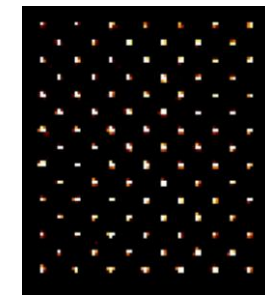
Trapped ions



Quantum gas microscopes

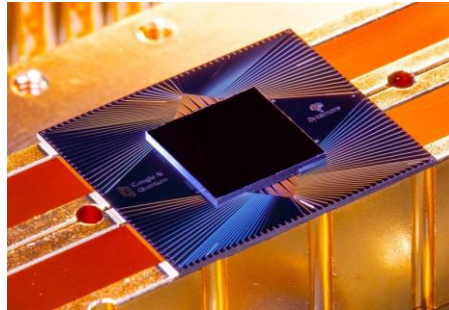


Rydberg tweezer arrays

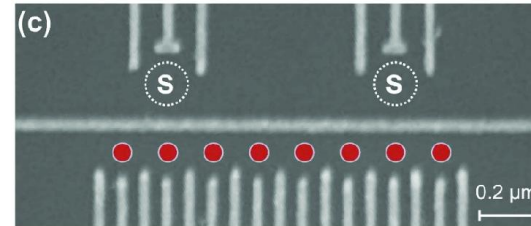


Many platforms

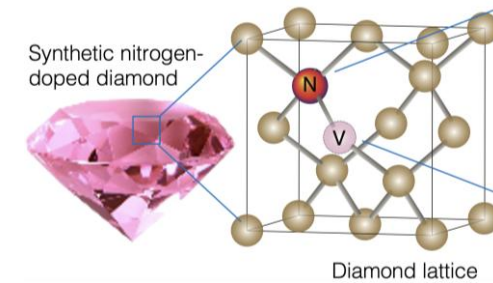
Superconducting qubits



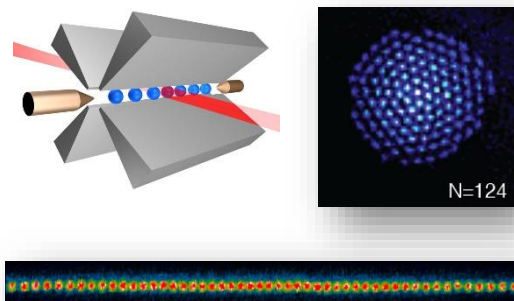
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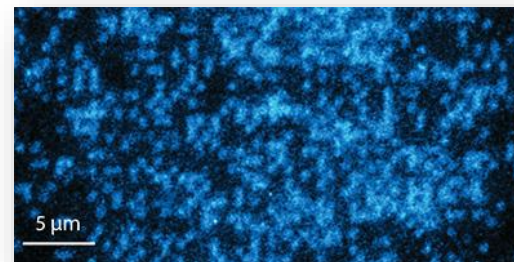
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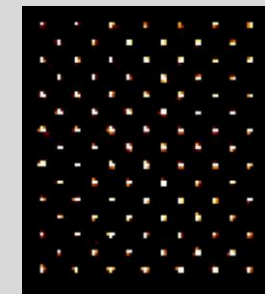
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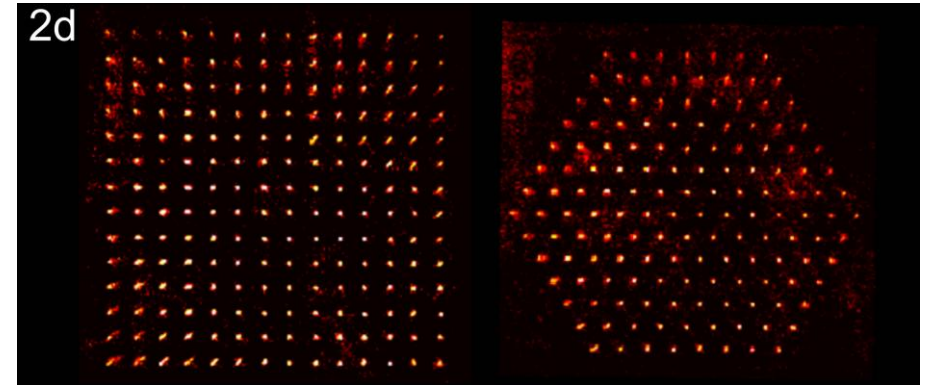
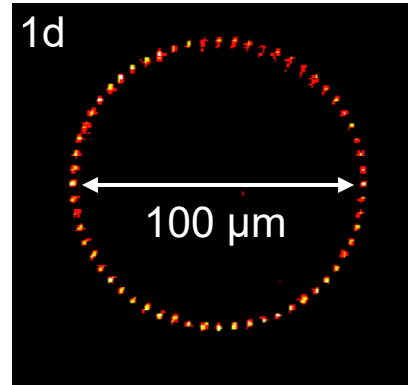
Rydberg atom arrays

- **Arrays of single atoms**

Full control of geometry in 2D

Up to 500 atoms

Spacing: a few microns



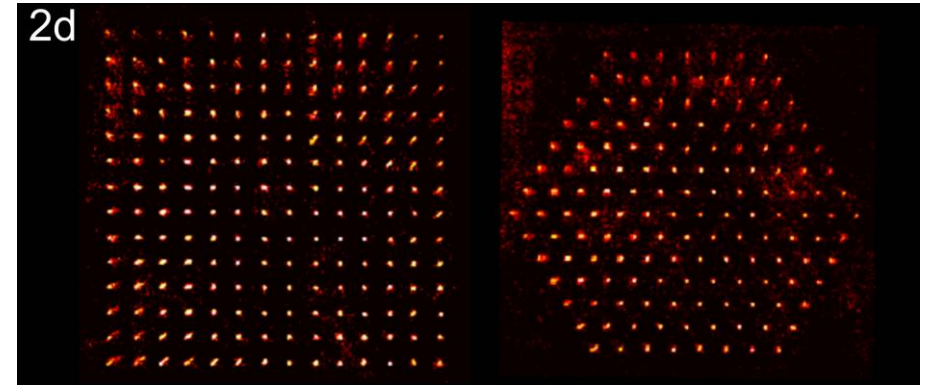
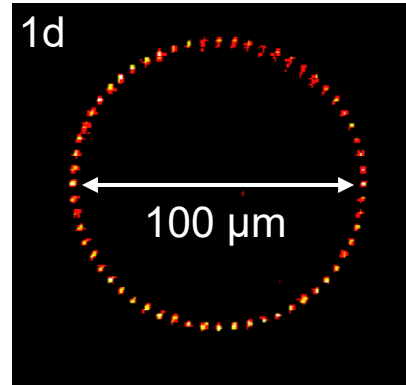
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- **Strong interactions via Rydberg excitation**

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

Lifetime: 100 to 200 μs

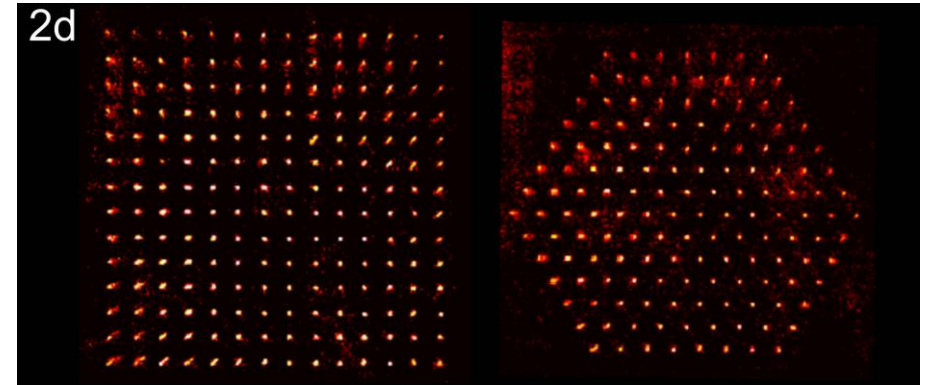
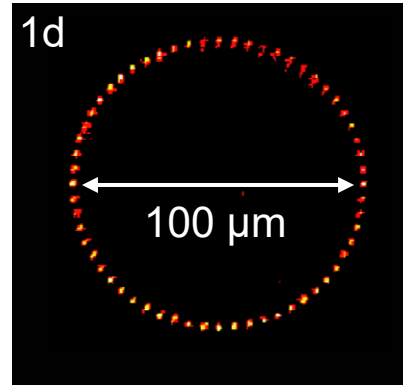
Rydberg atom arrays

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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 μs

- ***Implement quantum gates***

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

Ising (van der Waals interactions)

XY (resonant dipole-dipole interaction)

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...

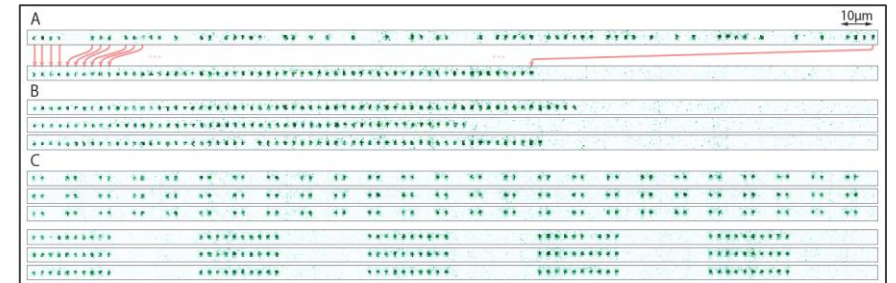
Rydberg atoms and optical tweezers

2001: Single atoms in optical tweezers (Grangier)



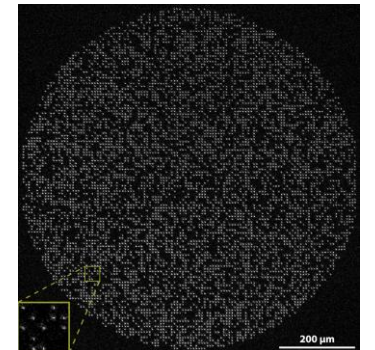
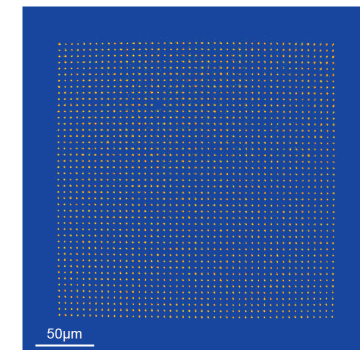
2009: Entanglement of 2 atoms with Rydberg blockade (Browaeys, Saffman)

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

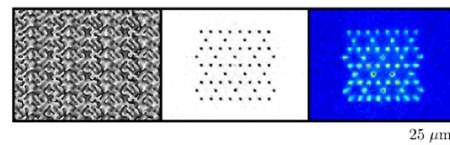


2021: Quantum simulations of Ising model with 200+ atoms (Browaeys, Lukin)

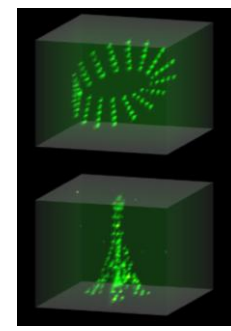
2024: Logical qubits (Lukin)
Large arrays > 2000 atoms (Endres, Pan)



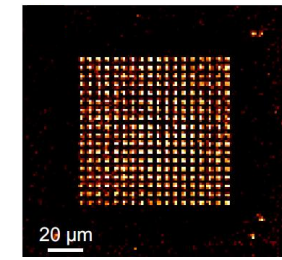
Single atoms in tweezers
Schlosser *et al.*



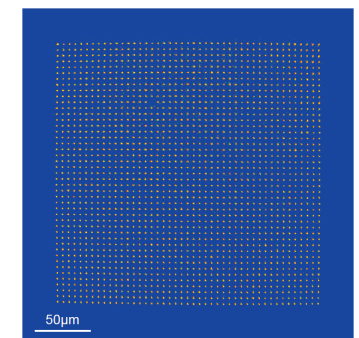
Large holographic arrays
Nogrette *et al.*



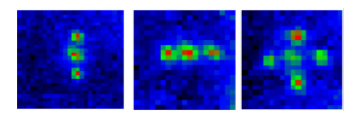
3D arrays
Barredo *et al.*



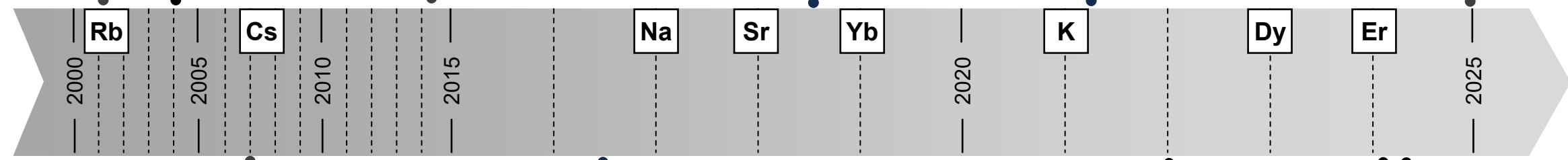
Cryogenic array
Schymik *et al.*



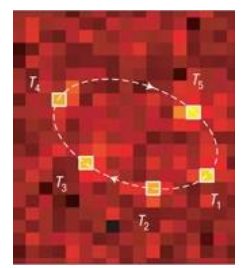
2024-atom rearranged array
Lin *et al.*



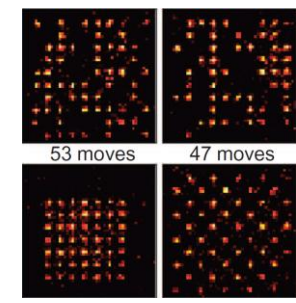
First holographic arrays
Bergamini *et al.*



Moving qubits
Beugnon *et al.*



Atom-by-atom
rearrangement
Barredo *et al.*
Endres *et al.*



A

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	100
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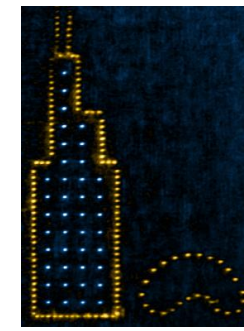
B

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	100
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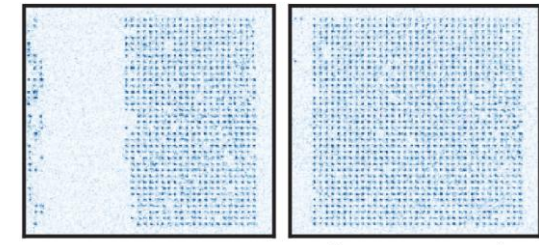
C

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	100
---	---	---	---	---	---	---	---	---	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	----	-----

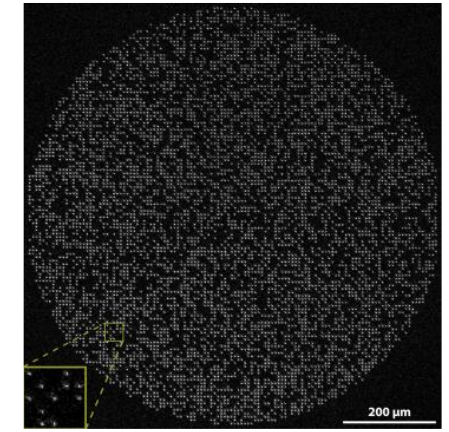
Dual species arrays
Singh *et al.*



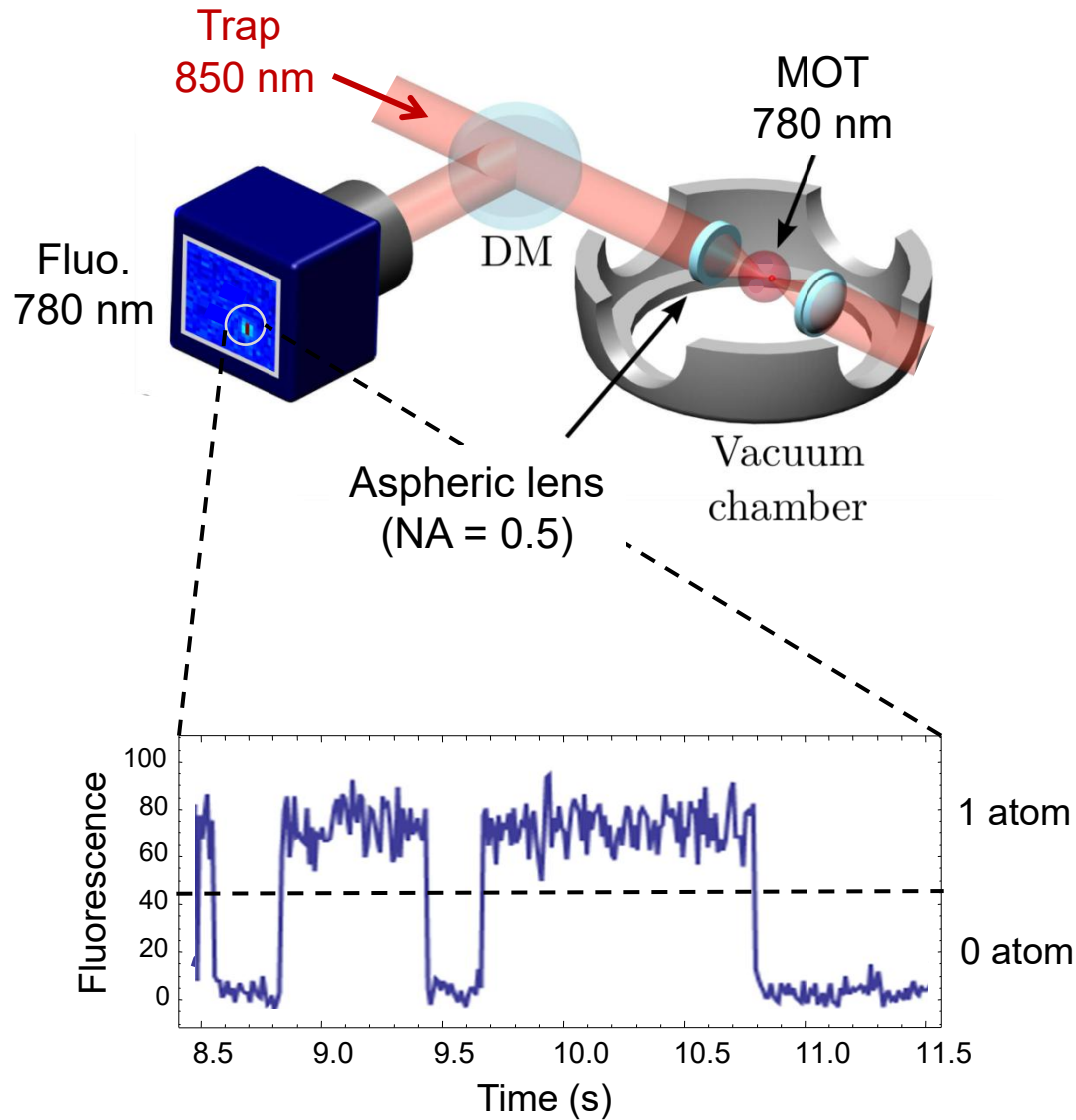
Iterative assembly
Norcia *et al.*



6100 qubits
Manetsch *et al.*



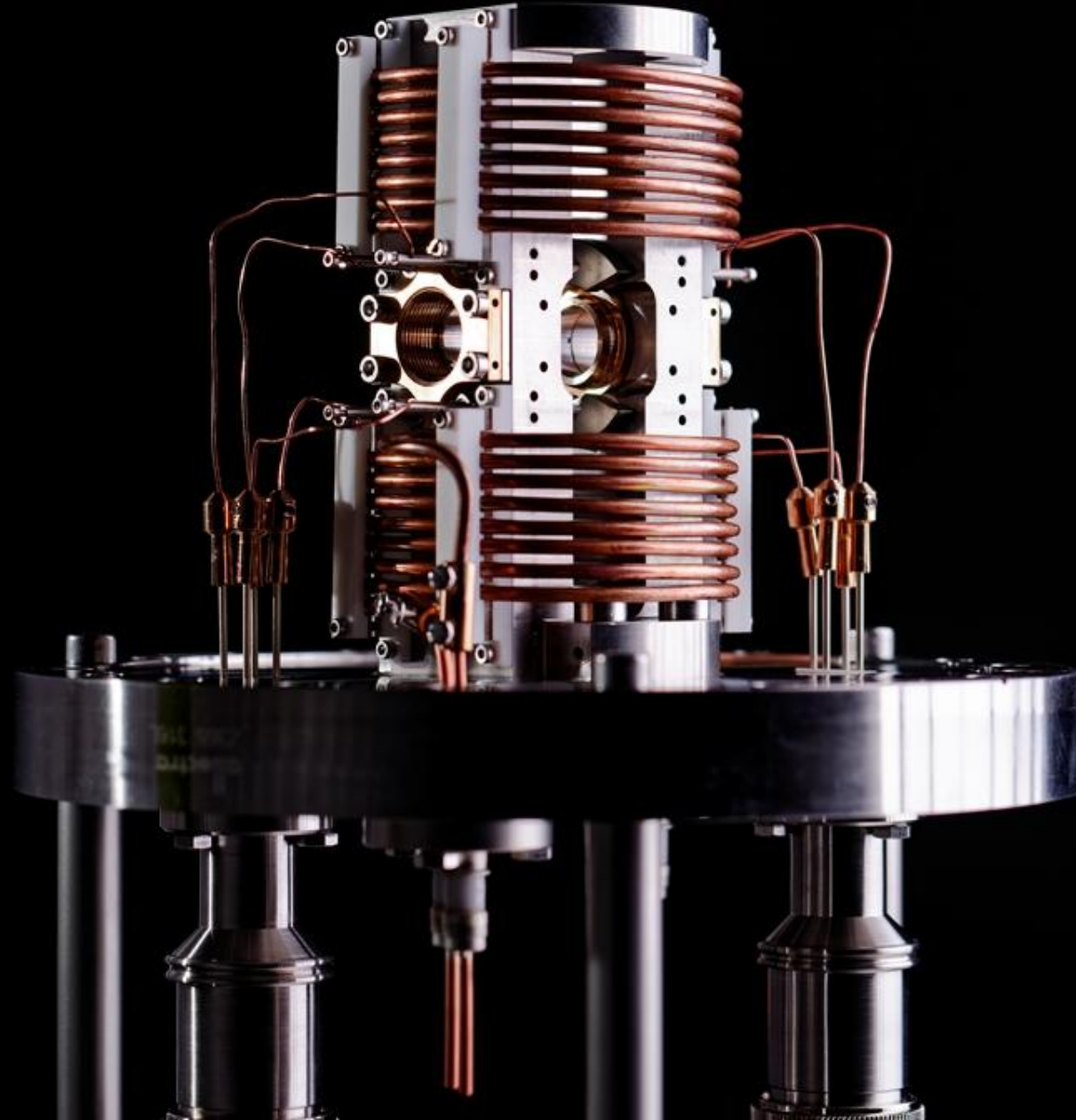
Single atoms in optical tweezers



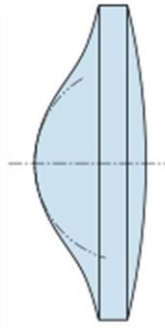
- 1 μm waist optical tweezers loaded from MOT
- At most one atom due to light-assisted collisions
- 50-55% loading probability:

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

The CHADOQ experiment (2011-2025)



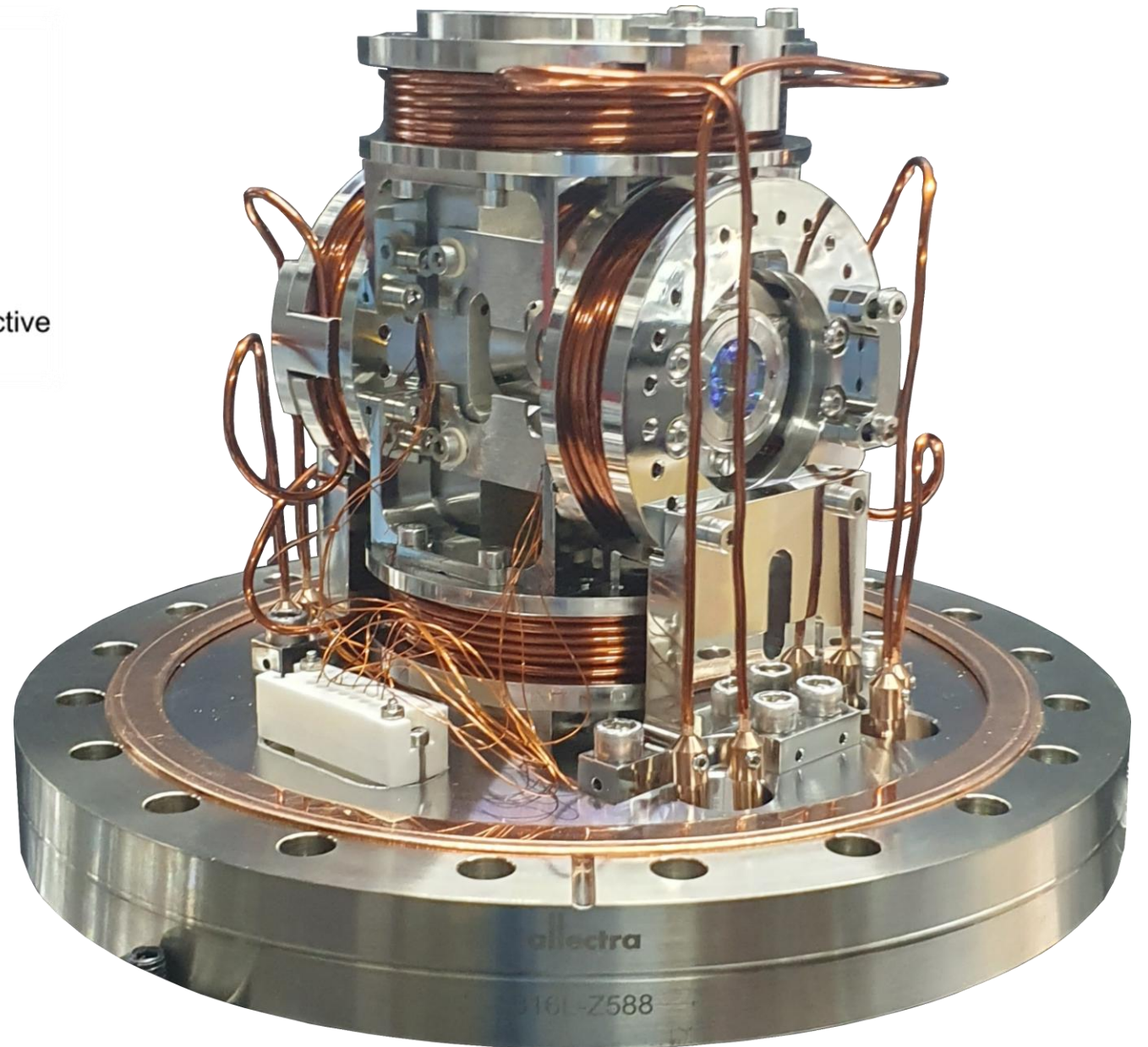
A new-generation setup



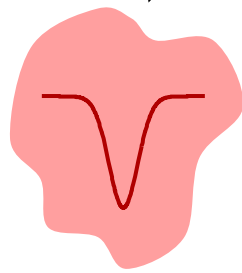
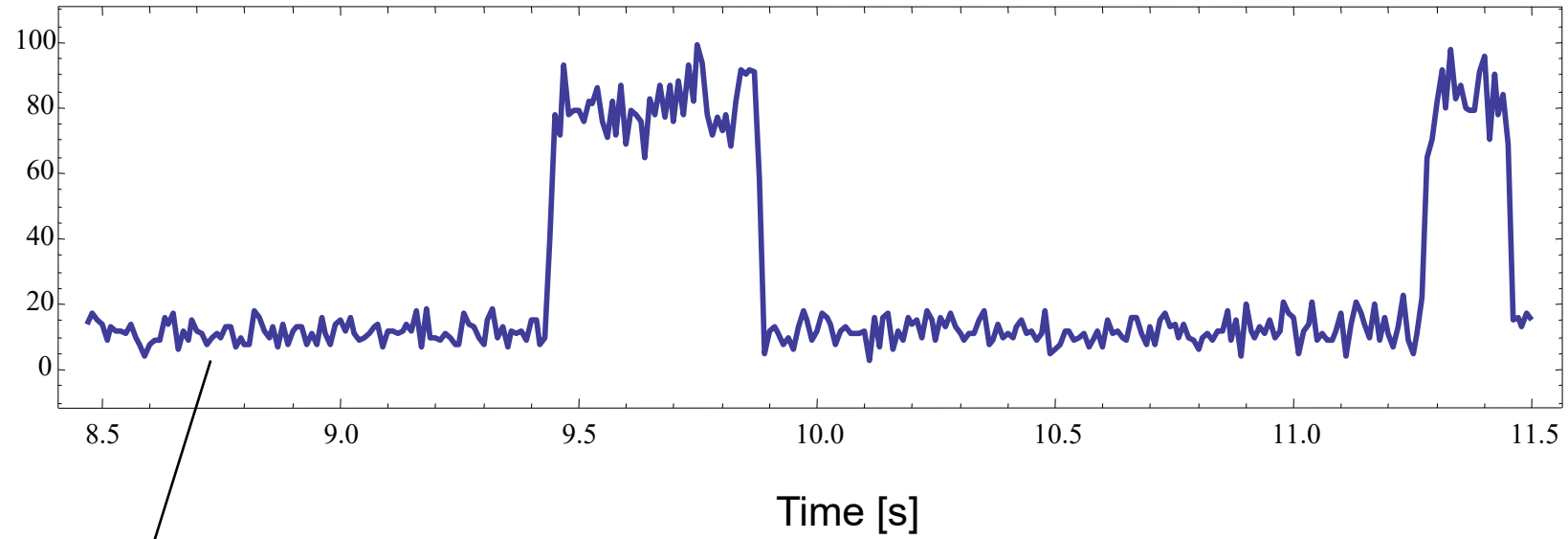
Aspheric lens



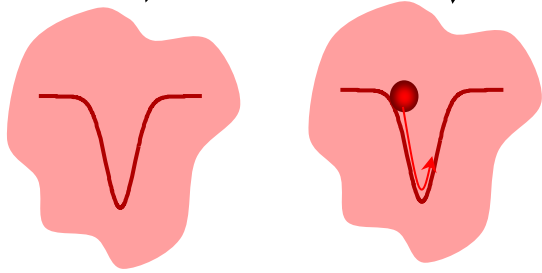
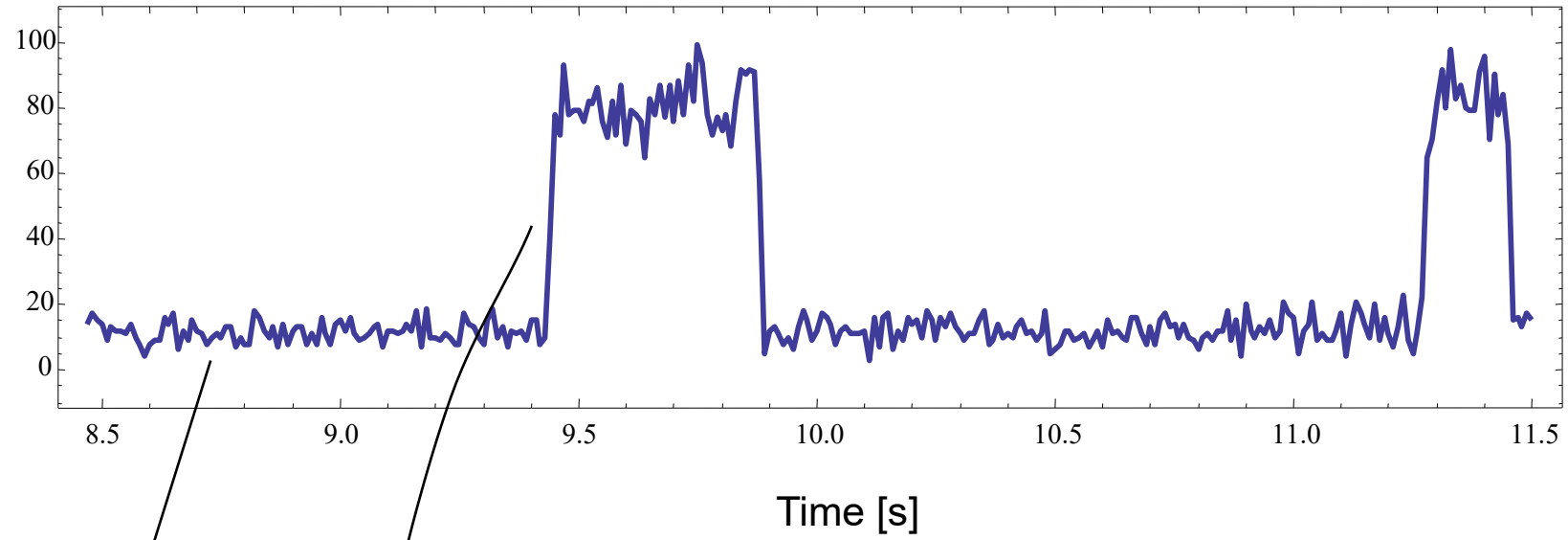
UHV compatible microscope objective
(Special Optics)



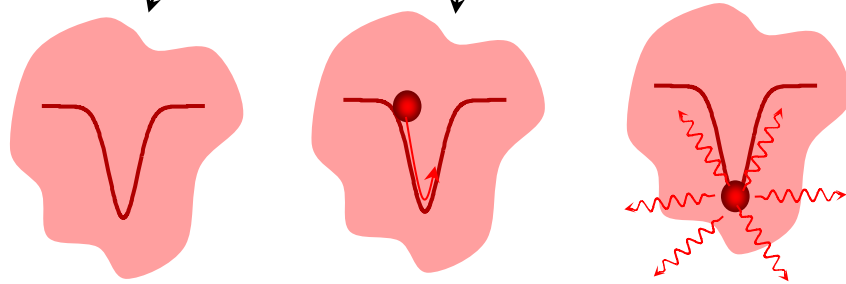
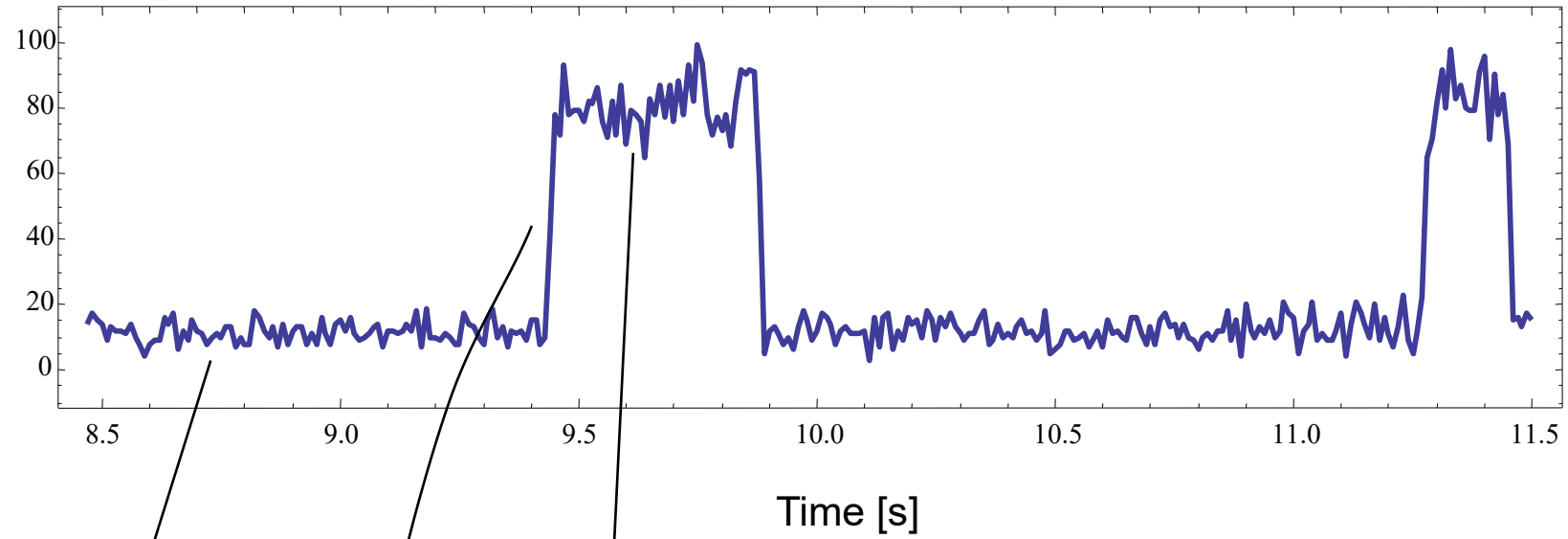
Why just zero or one atom?



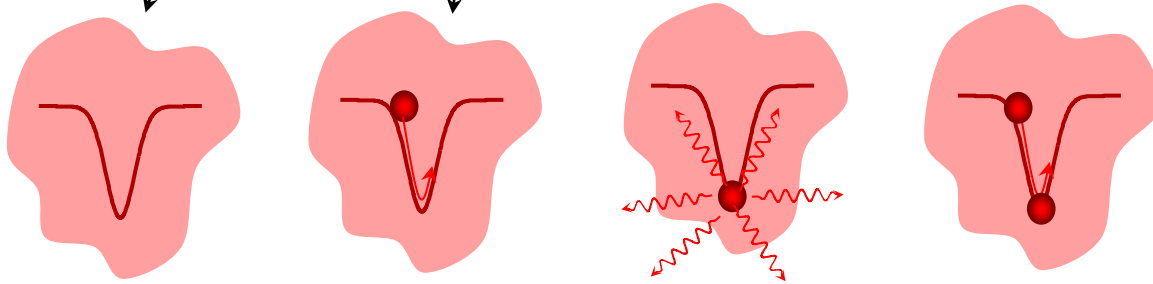
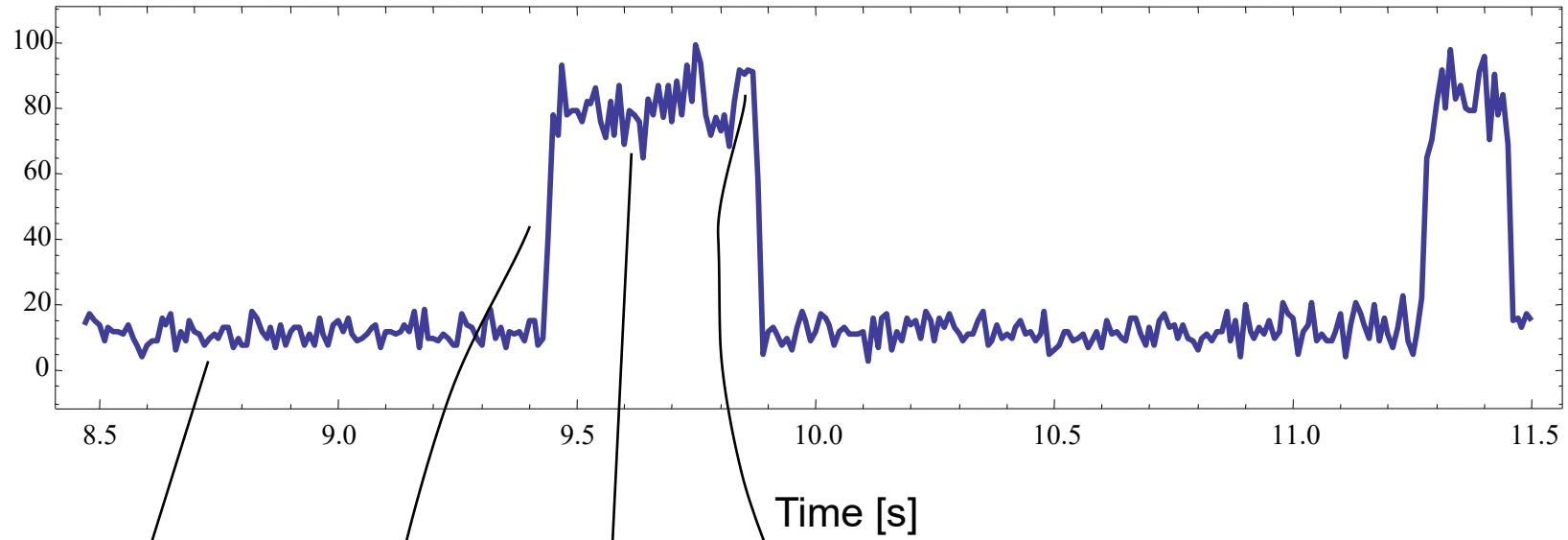
Why just zero or one atom?



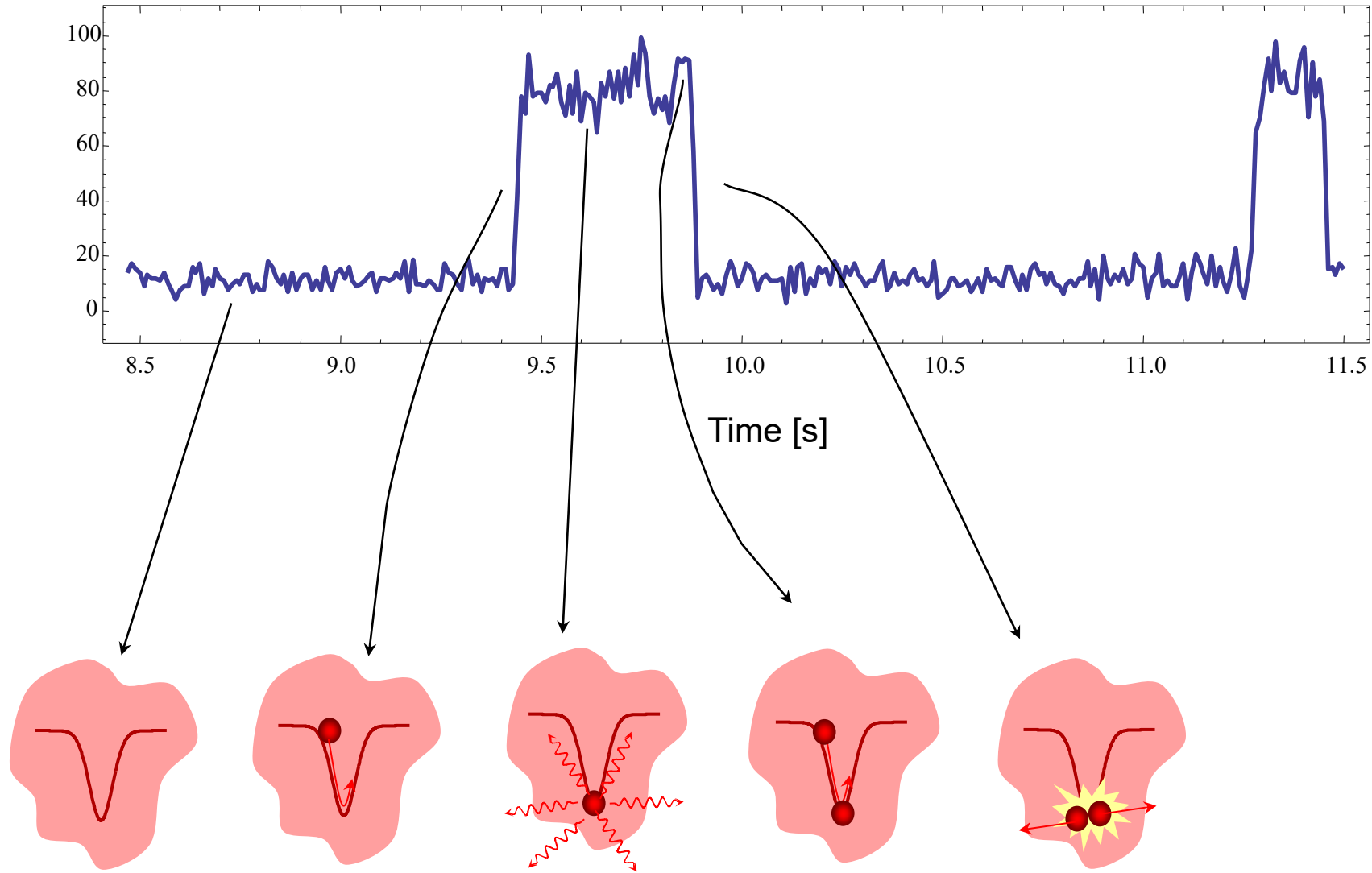
Why just zero or one atom?



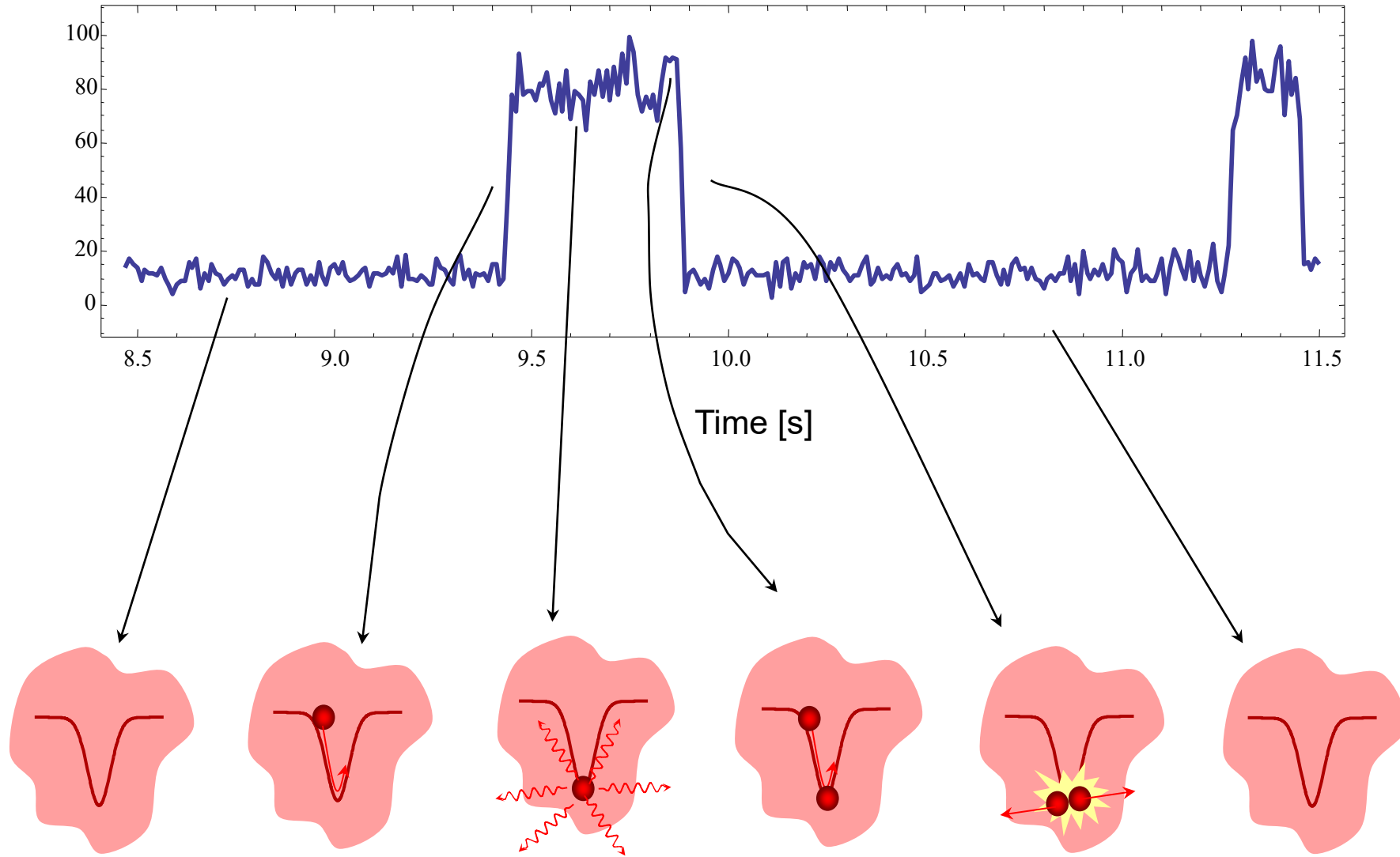
Why just zero or one atom?



Why just zero or one atom?



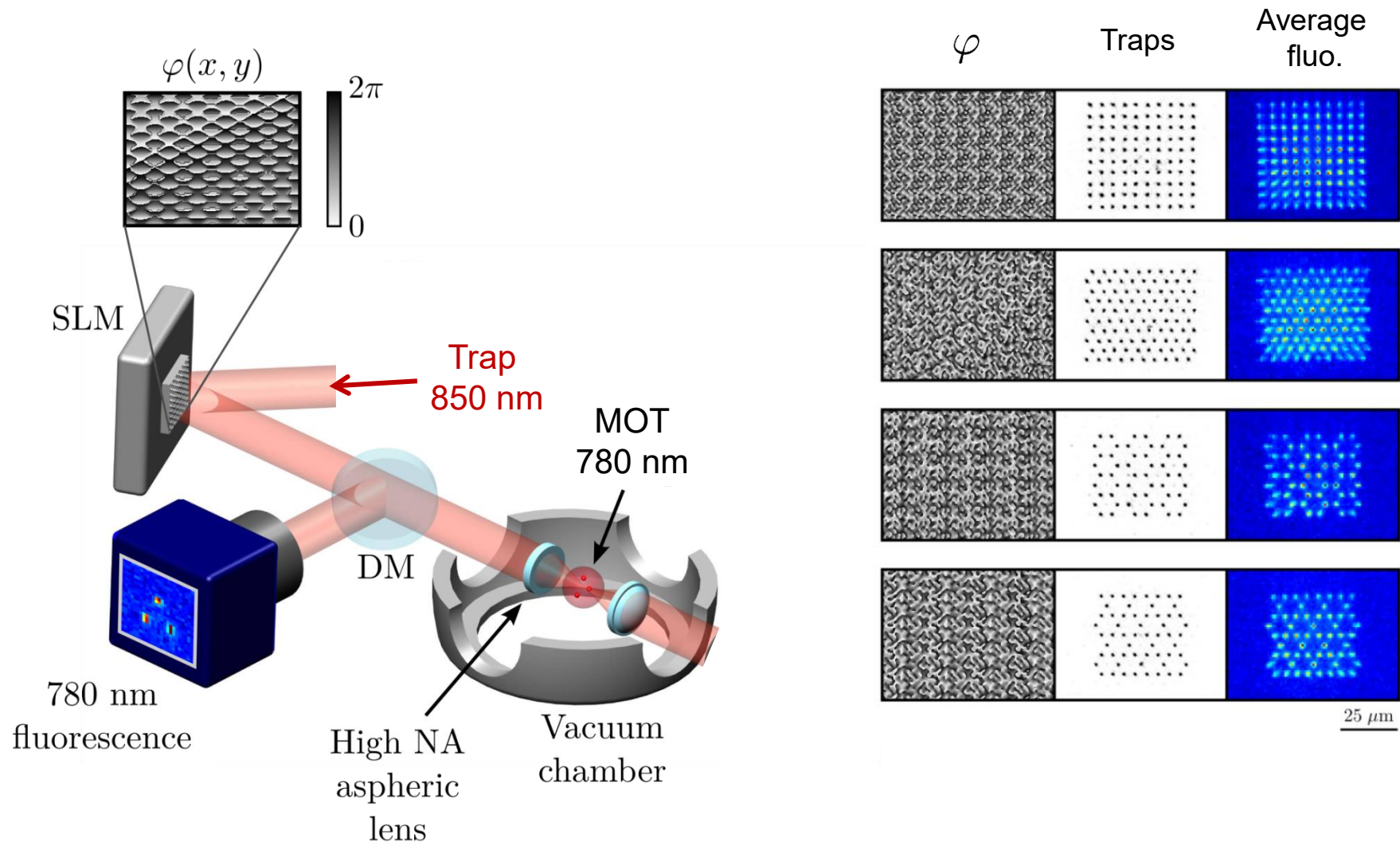
Why just zero or one atom?



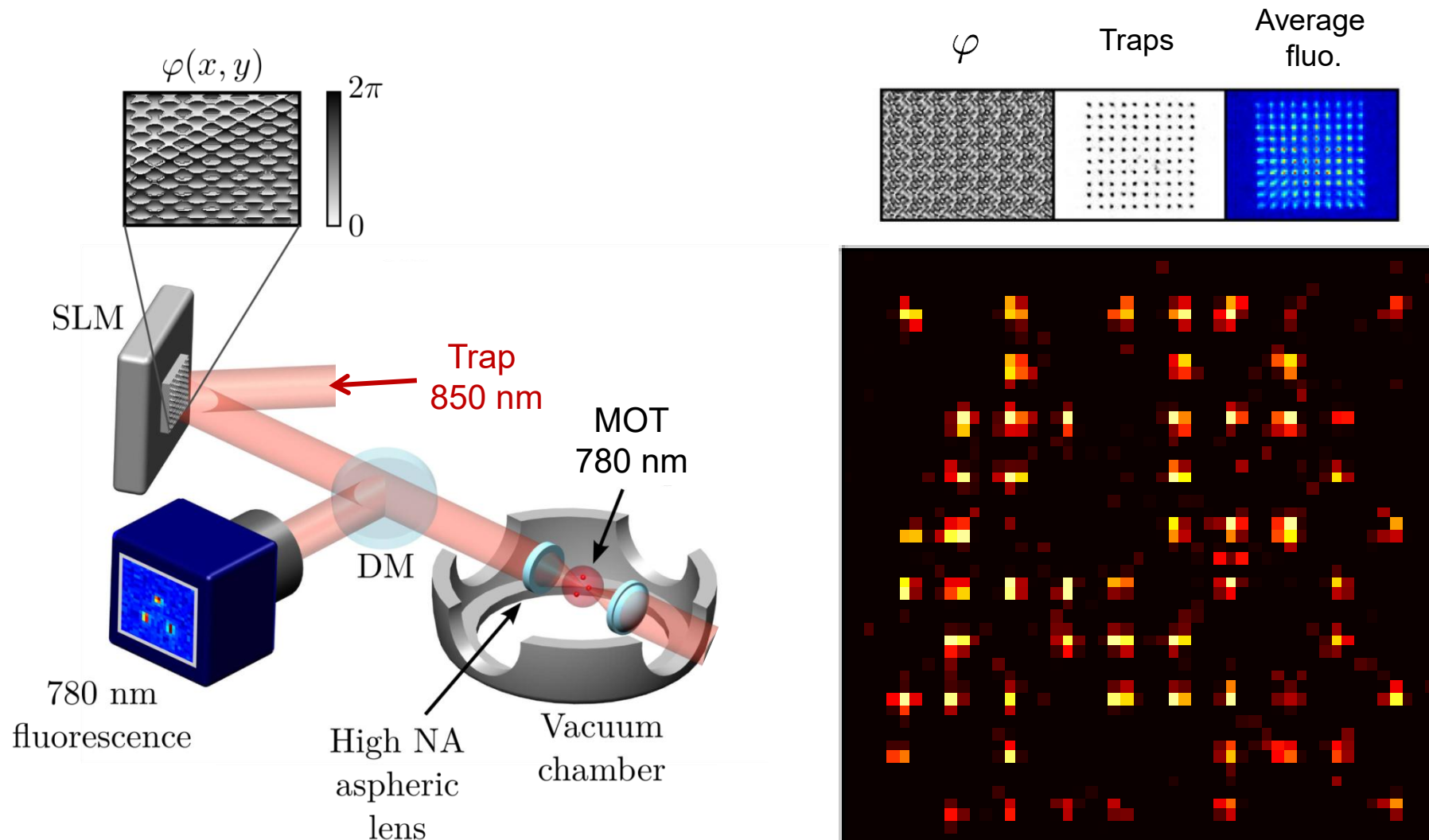
LECTURE 2

Tuesday, February 3rd, 2026

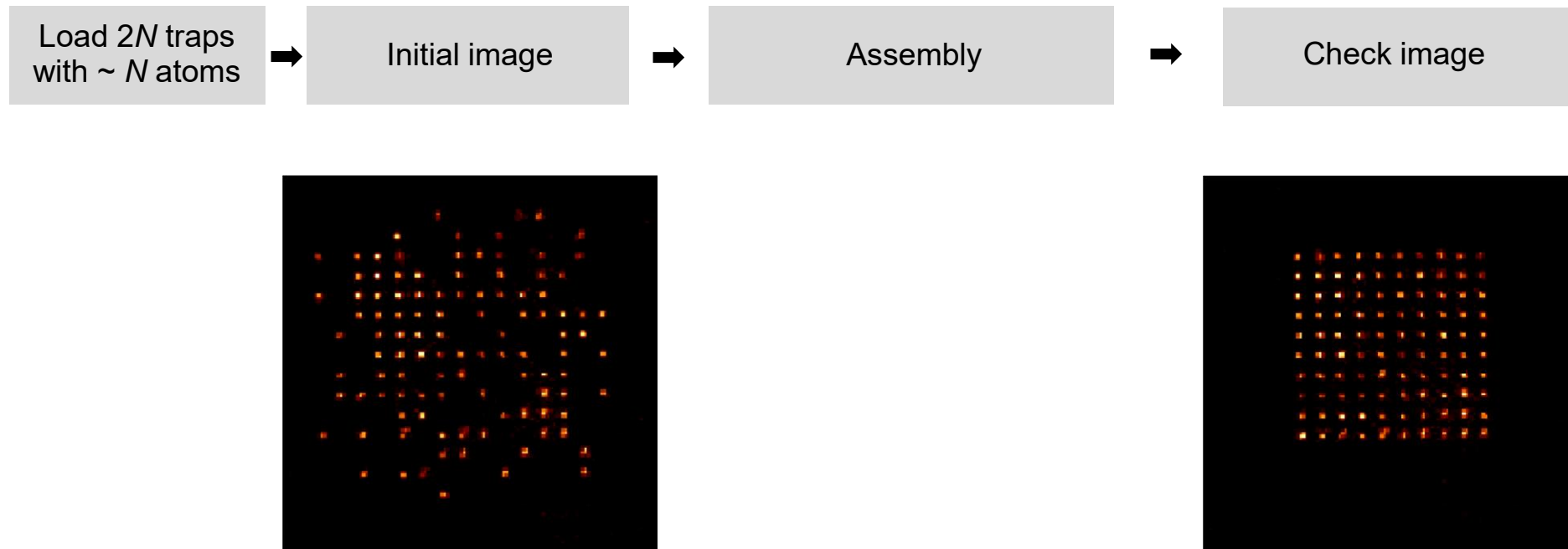
Arrays of single atoms



Arrays of single atoms



Atom-by-atom assembly



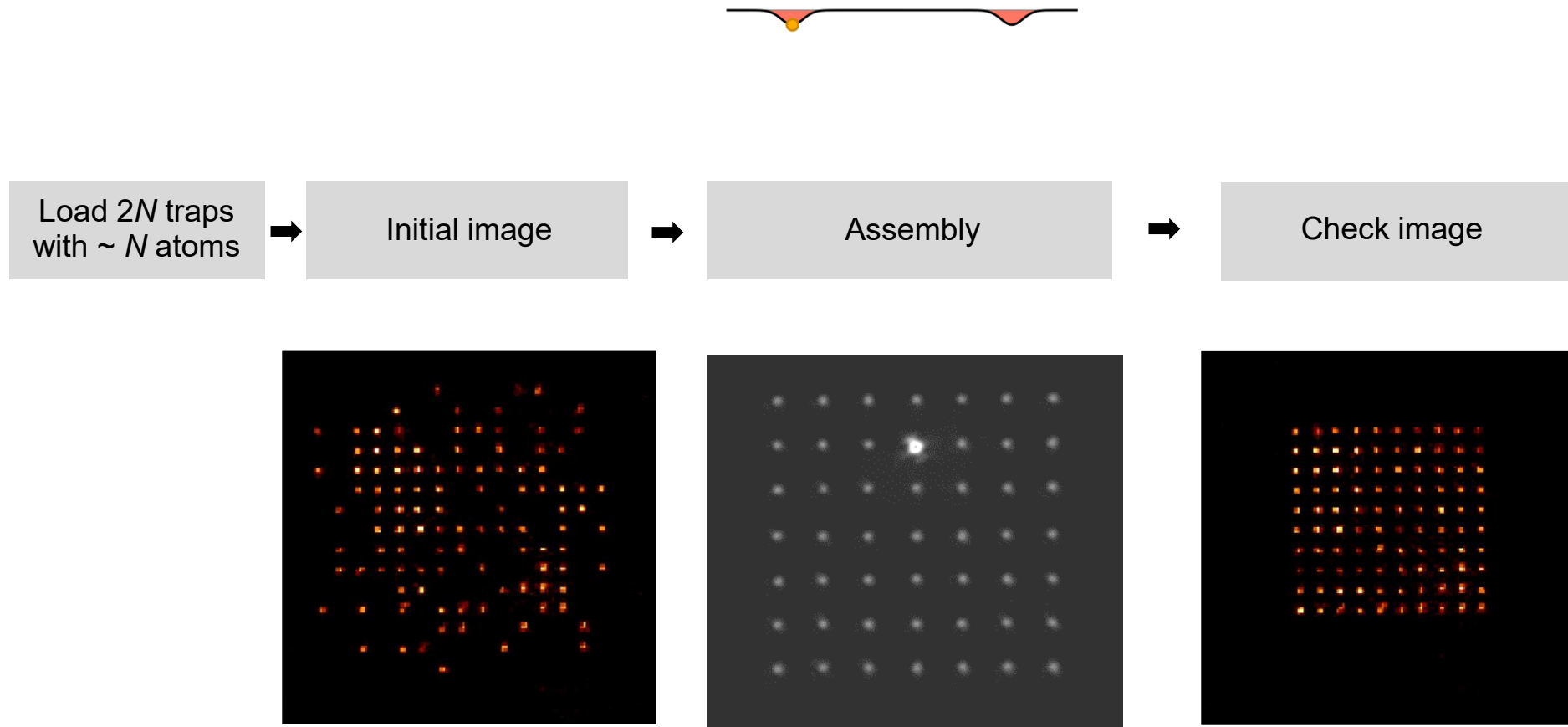
Barredo *et al.*, [Science](#) **354**, 1021 (2016)

See also:

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

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

Atom-by-atom assembly



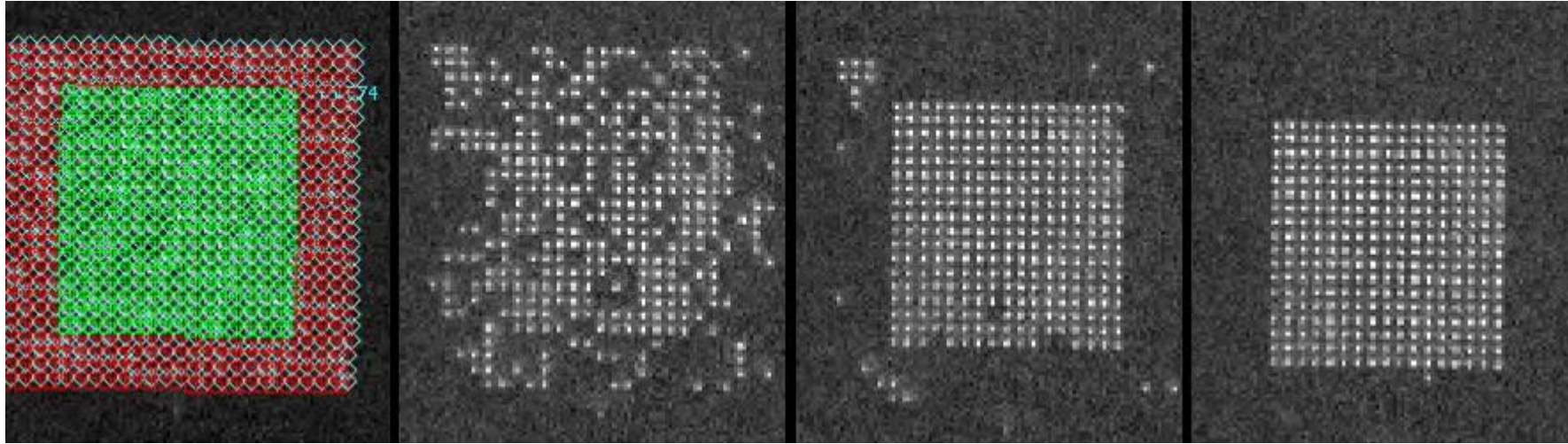
Barredo *et al.*, [Science](#) **354**, 1021 (2016)

See also:

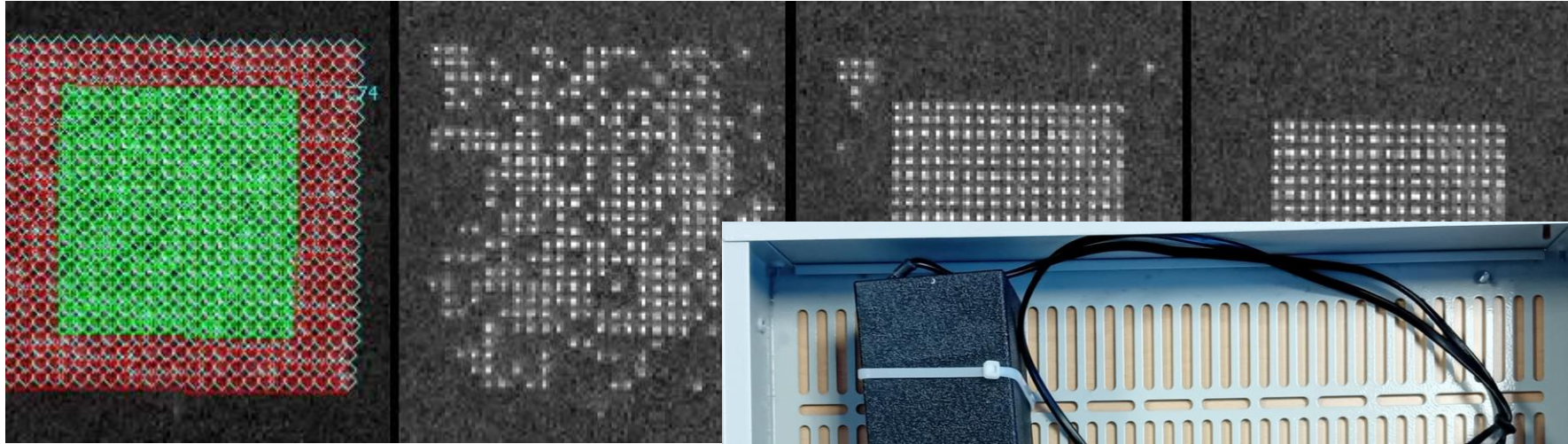
Endres *et al.*, [Science](#) **354**, 1024 (2016)

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

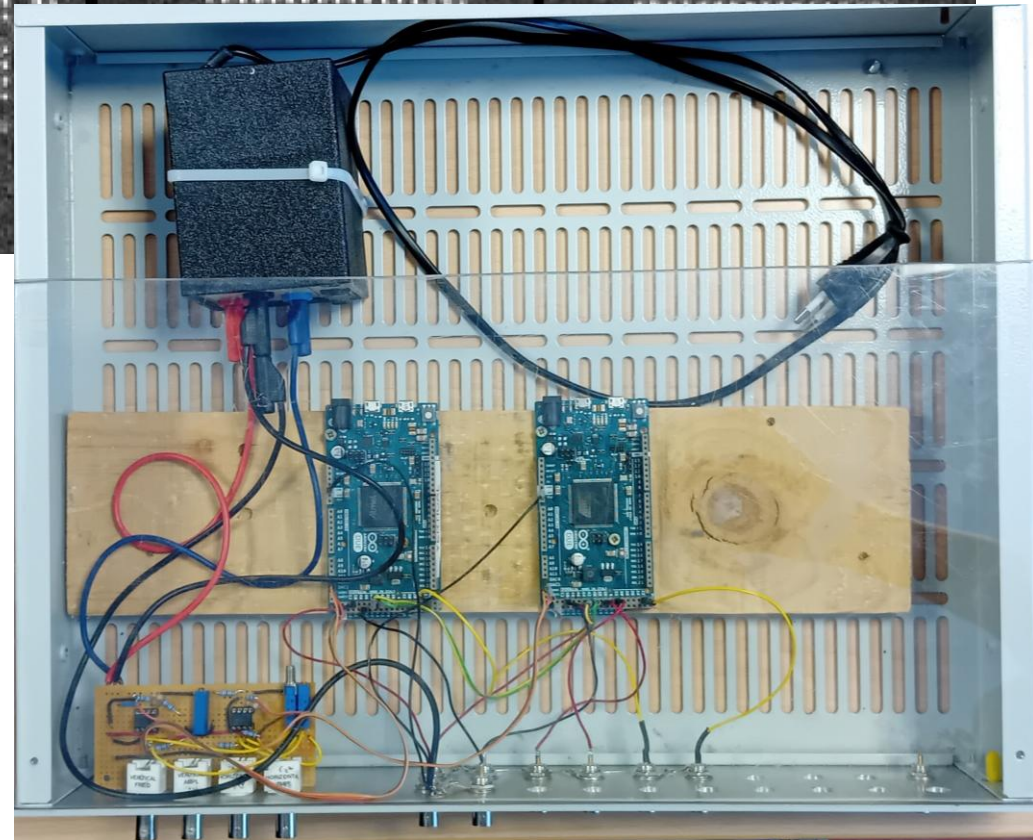
In practice in the lab



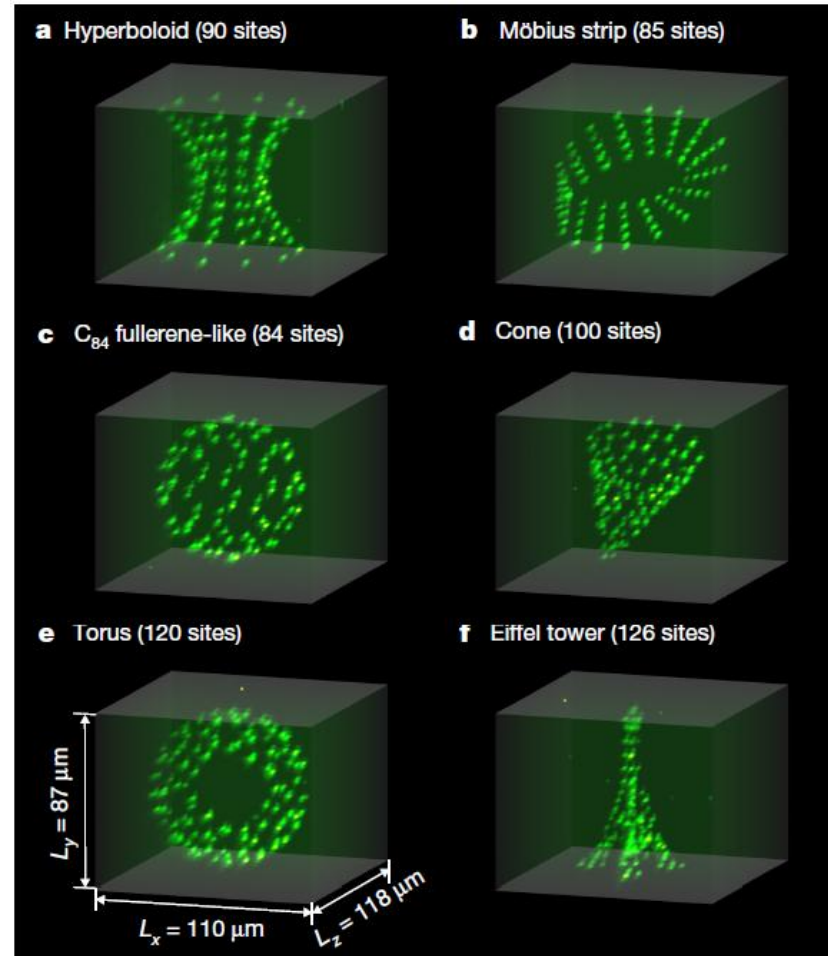
In practice in the lab



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



Extension to 3D arrays

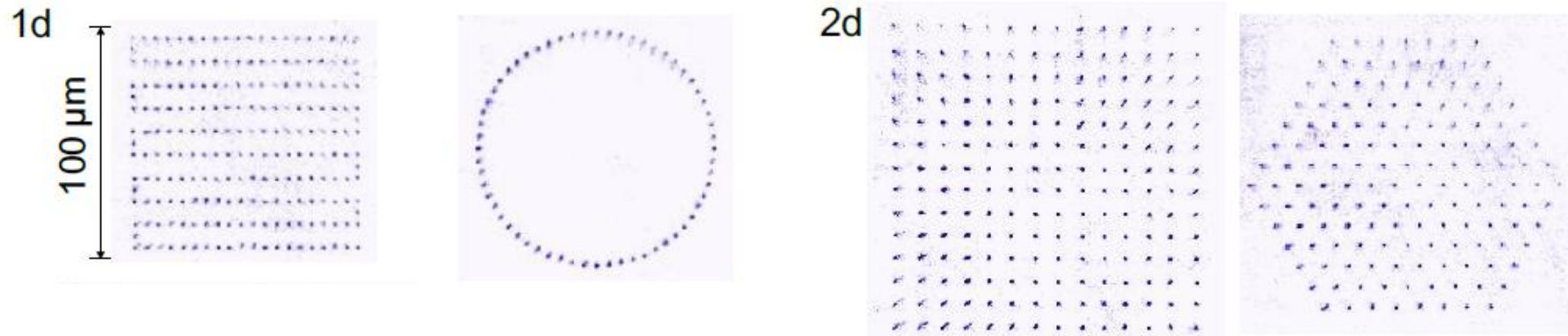


Improvements

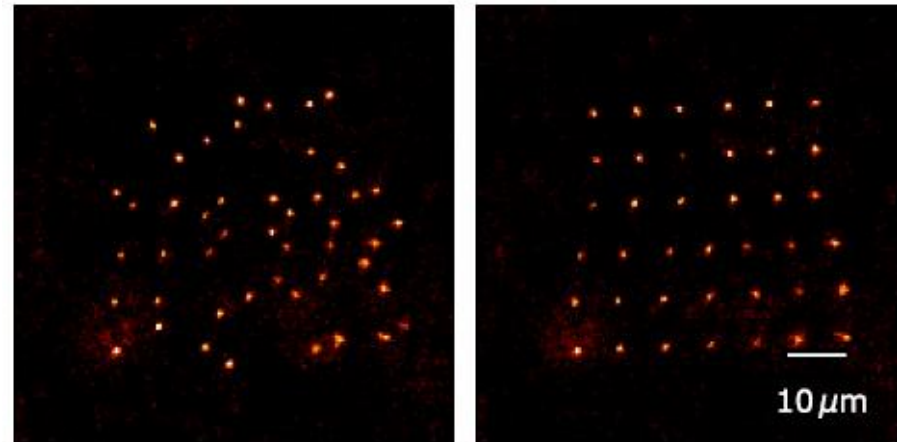
Improved assembler algorithms

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

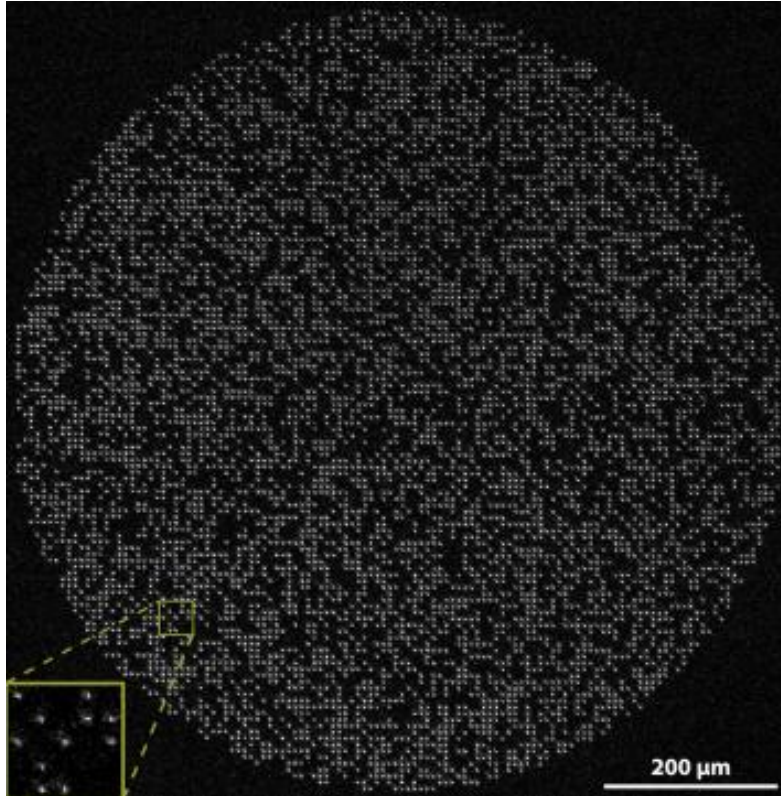
- **Up to > 200 atoms**



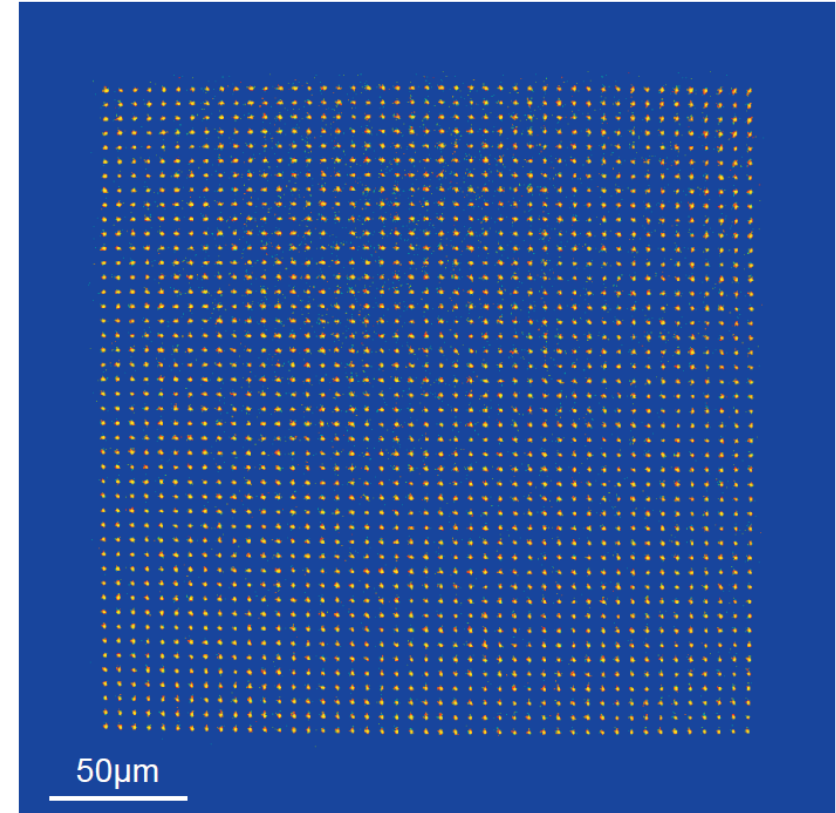
- **Geometries not limited to a regular array**



Current records

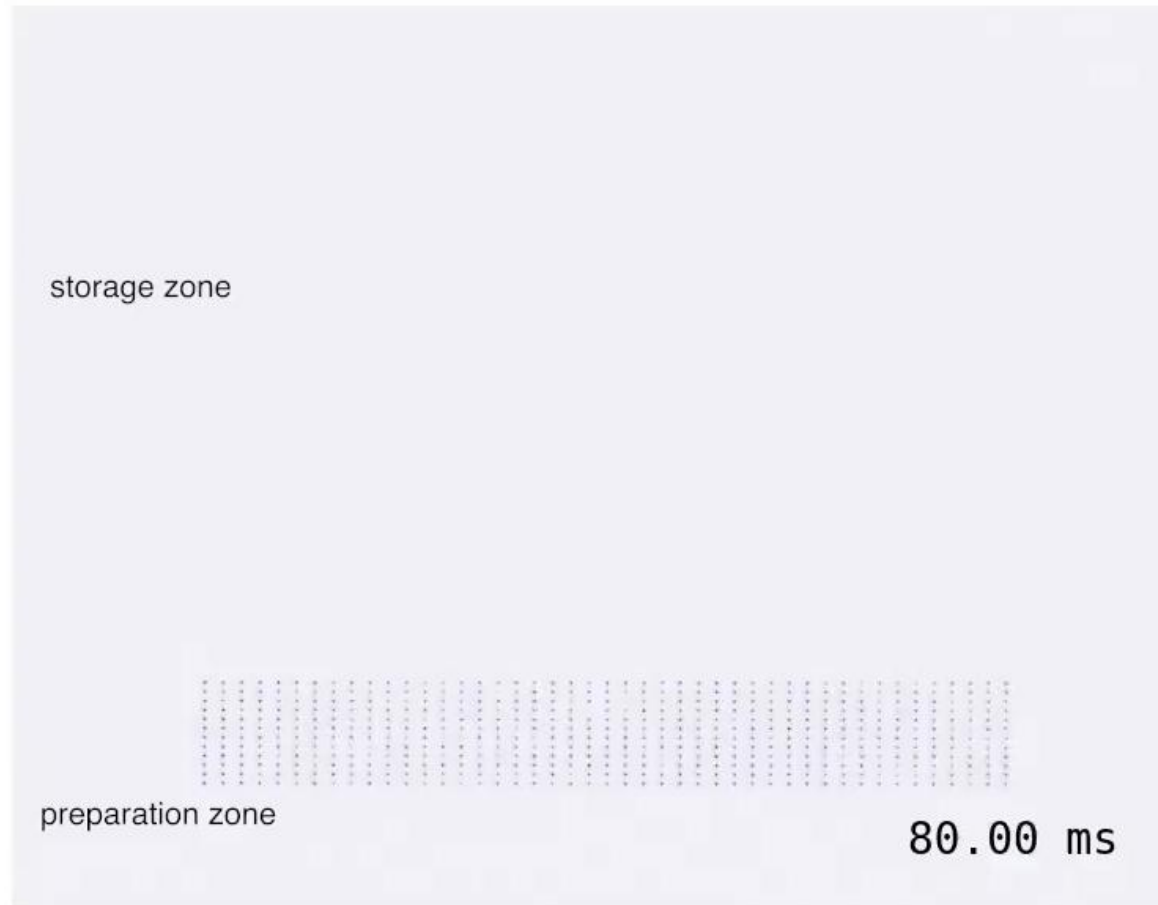


6100 qubits
Endres group, Caltech



2024-atom rearranged array
Pan group, Hefei

Continuous reloading

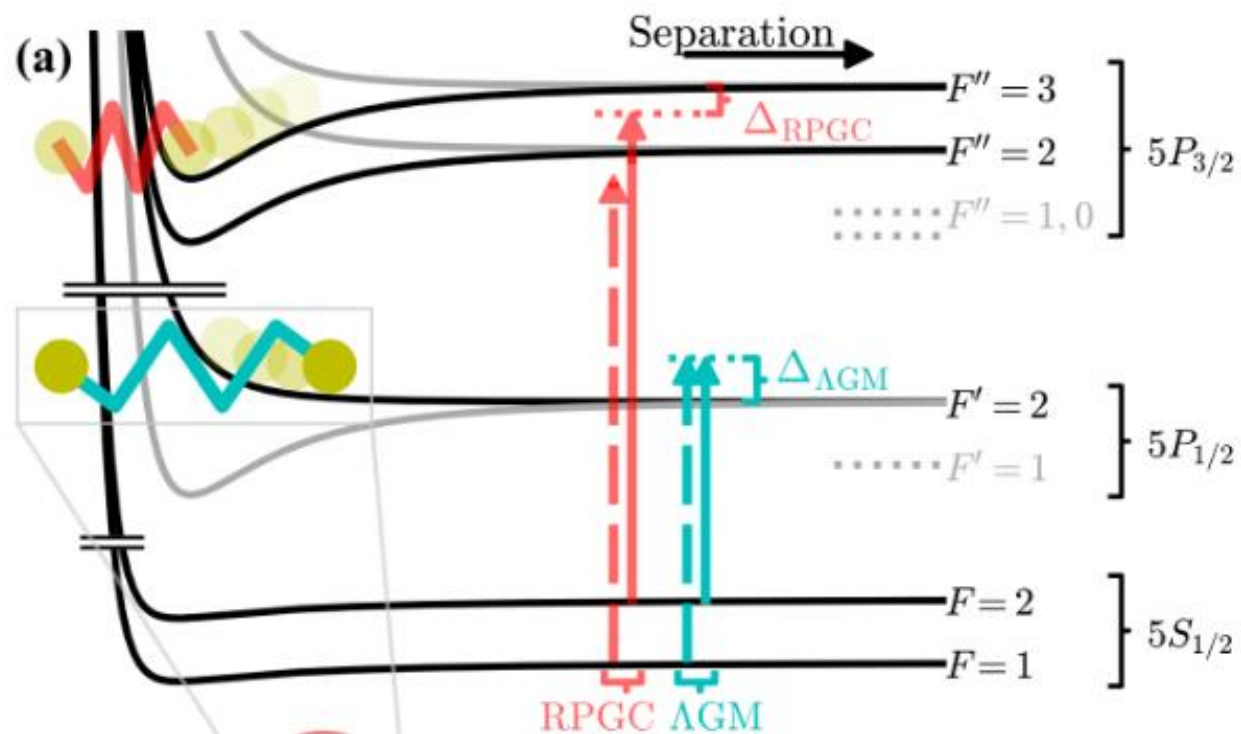


Lukin group, Harvard

Continuous operation of a coherent 3,000-qubit system

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

Enhanced loading with grey molasses

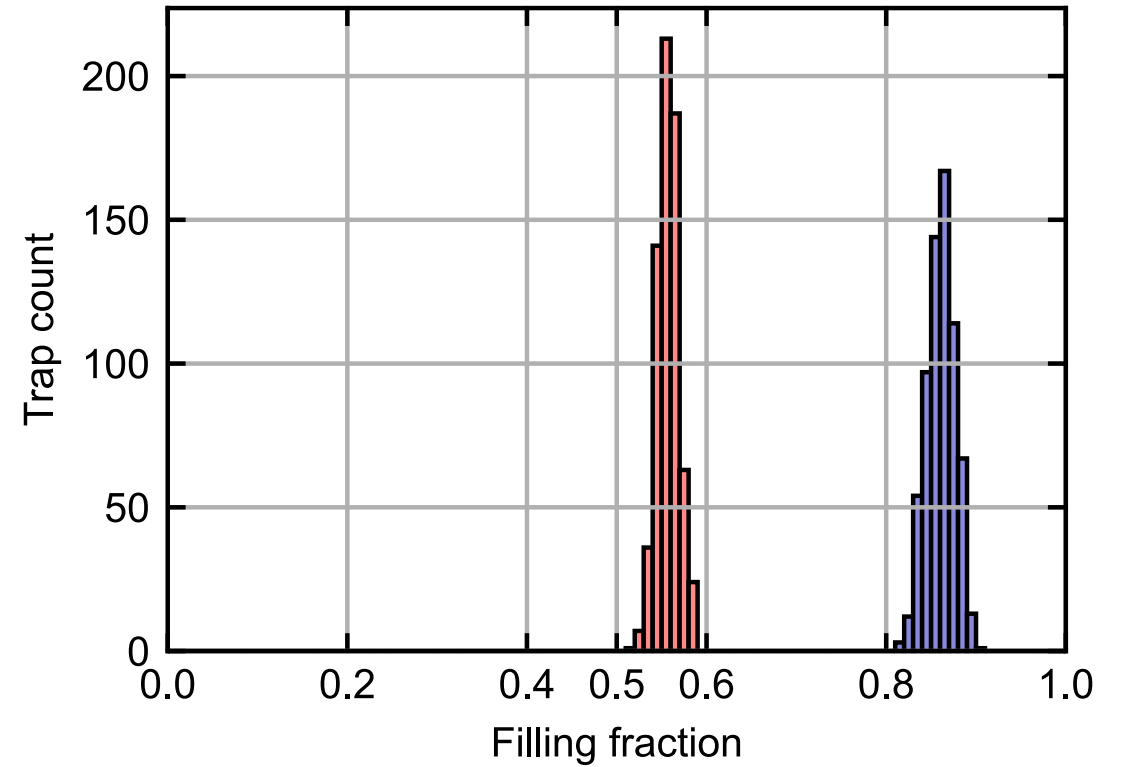
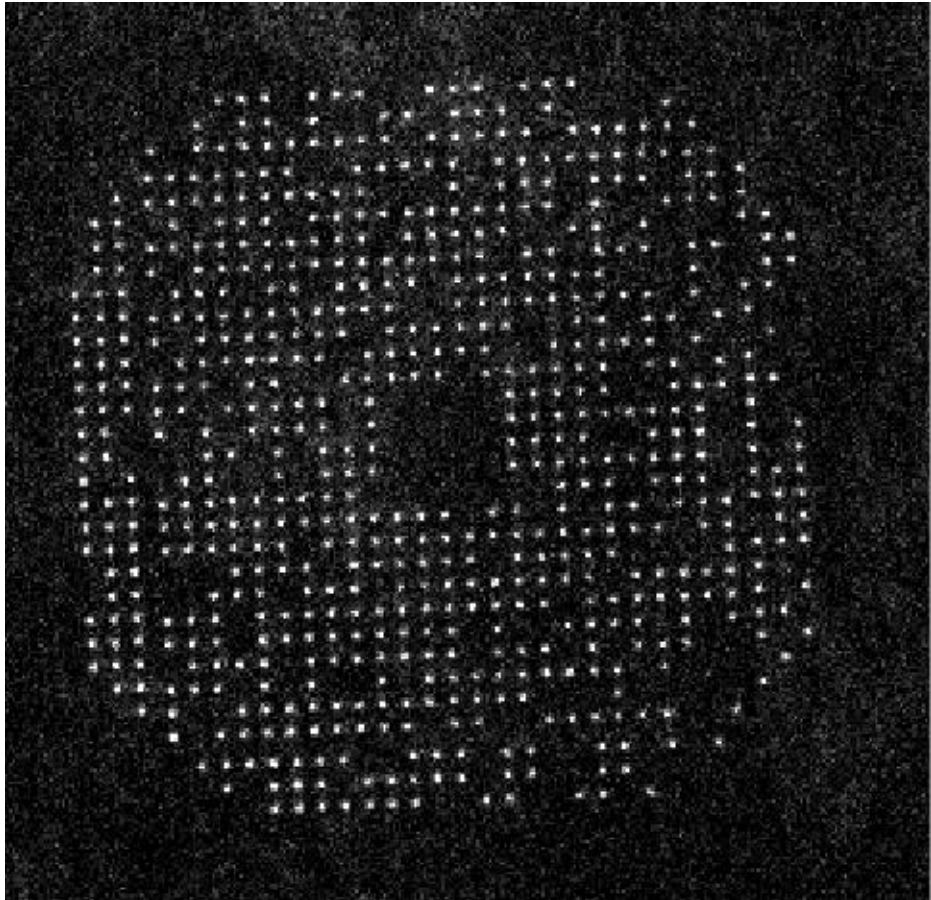


For $\Delta < 2 U_{\text{tweezer}}$, light-assisted collisions lead to the loss of a single atom!

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

Early work on blue-detuned collisions
Andersen group, Otago

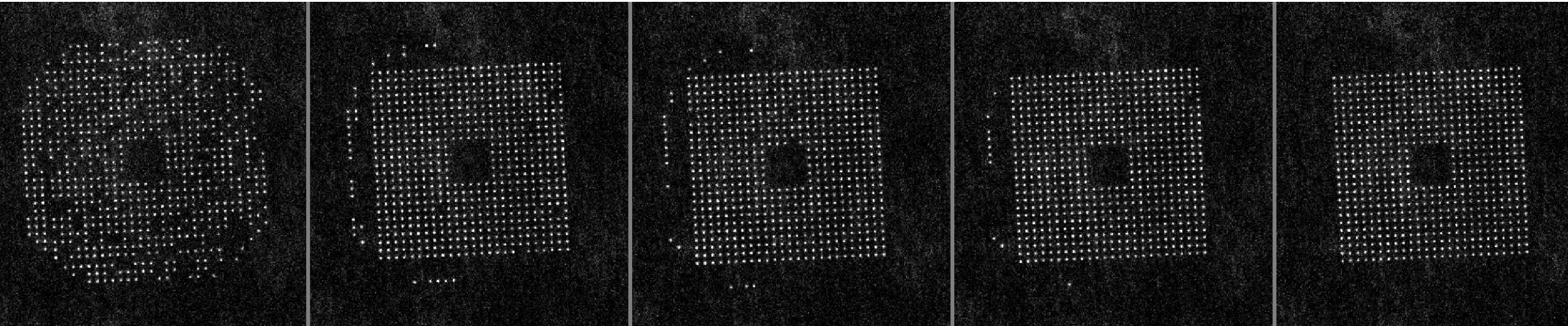
Enhanced loading in practice



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

600-atom array, defect-free

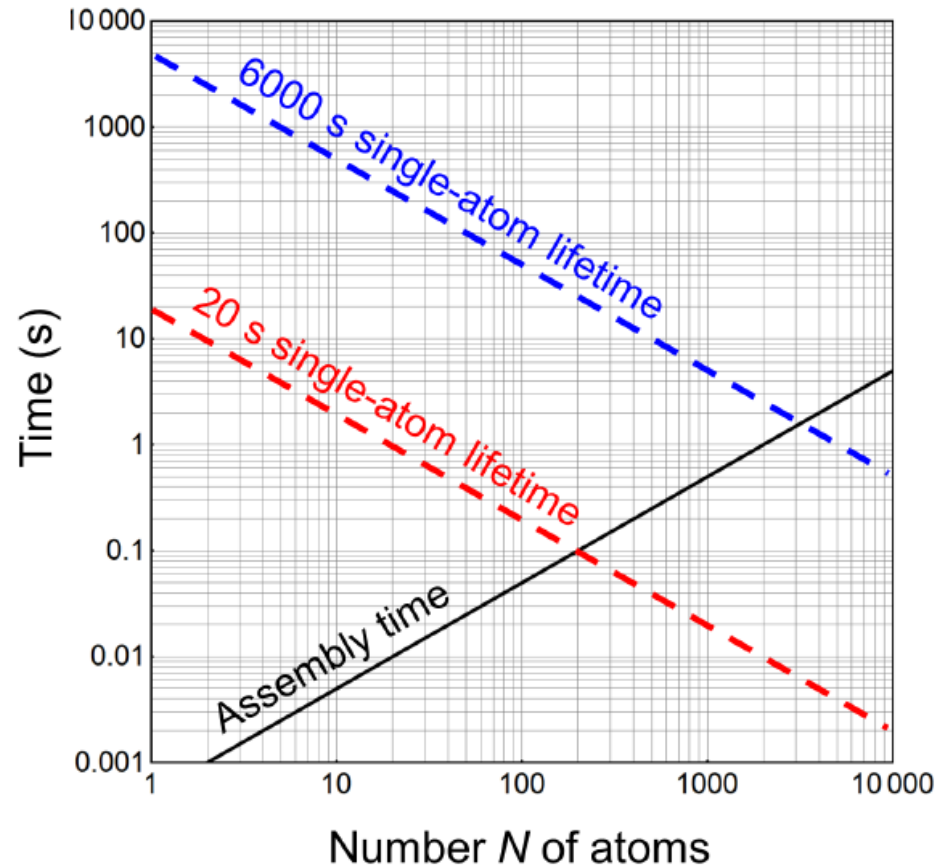
4 rearrangements cycles



Cryogenic arrays: why?

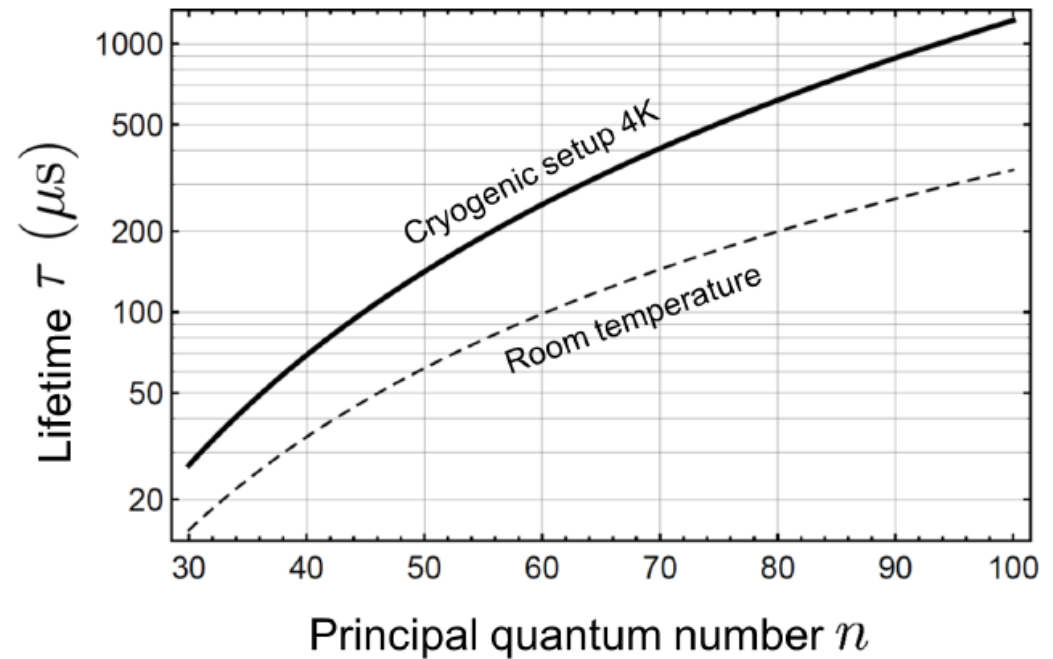
Better vacuum:

More time for assembly without defects



No black-body radiation:

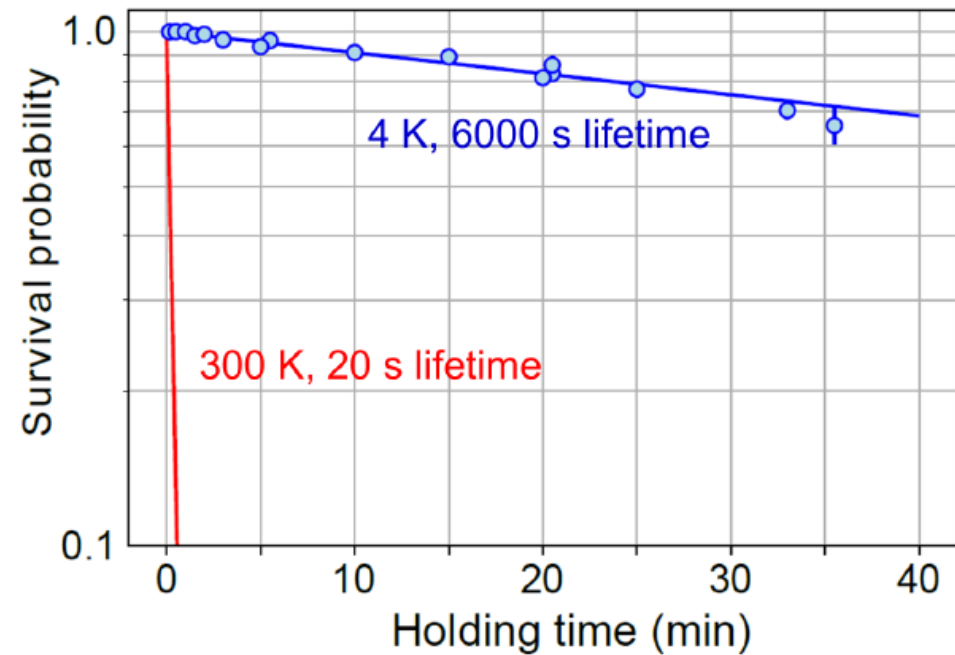
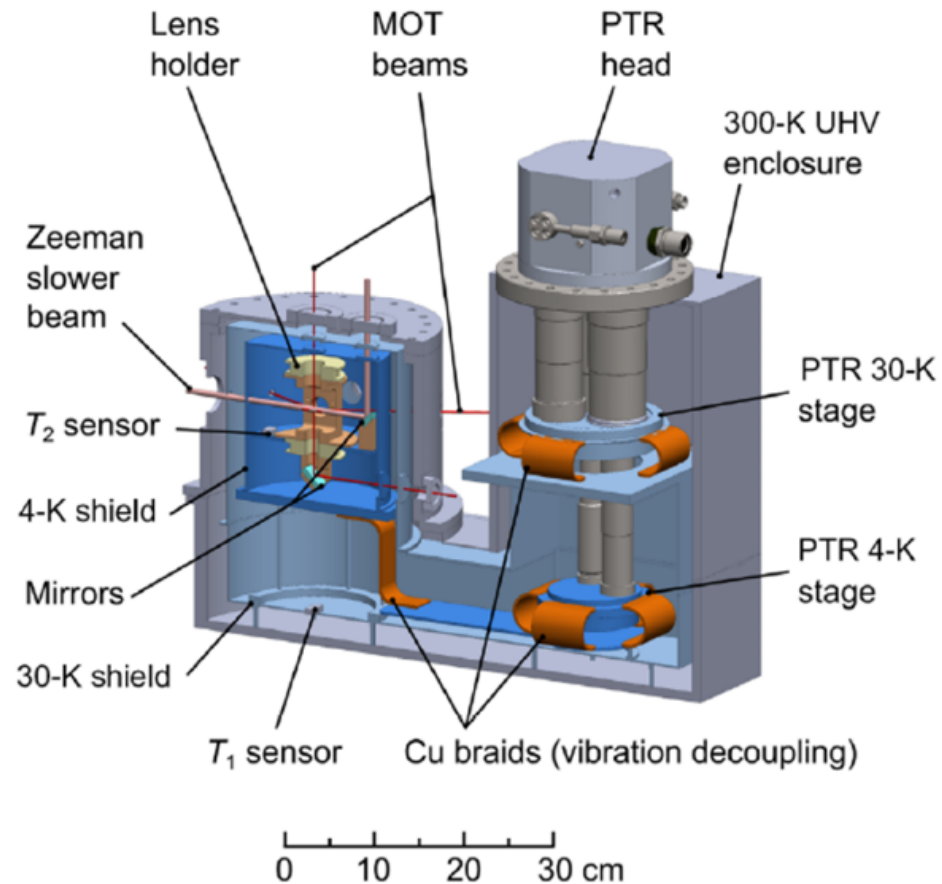
Longer Rydberg state lifetime



Cryogenic arrays: first demo

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

6000 s vacuum-limited lifetime in the tweezers!

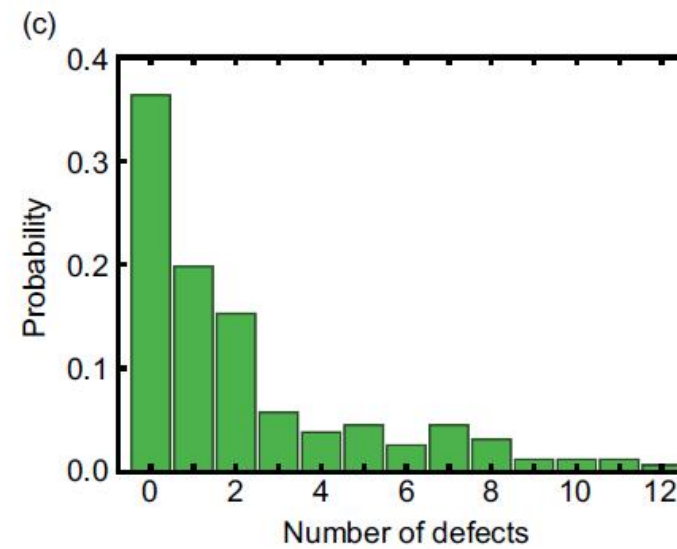
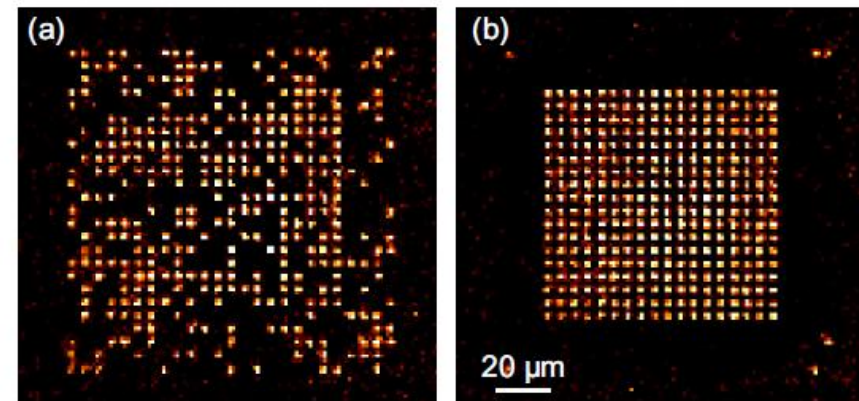


Cryogenic arrays: should be easy to go to large N !

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

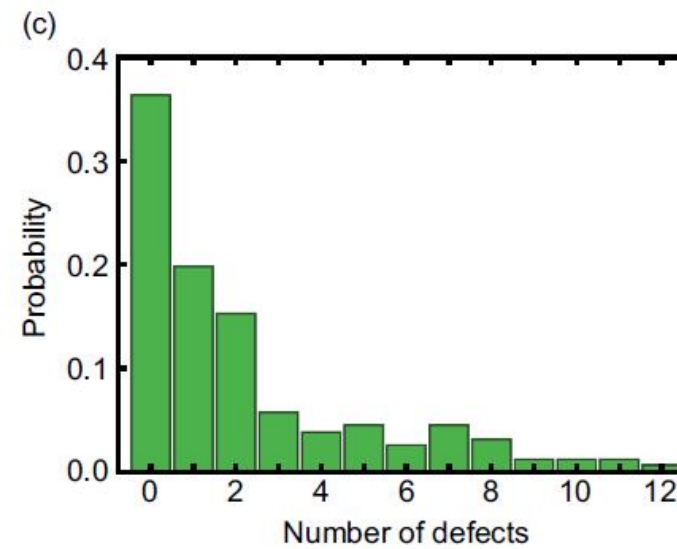
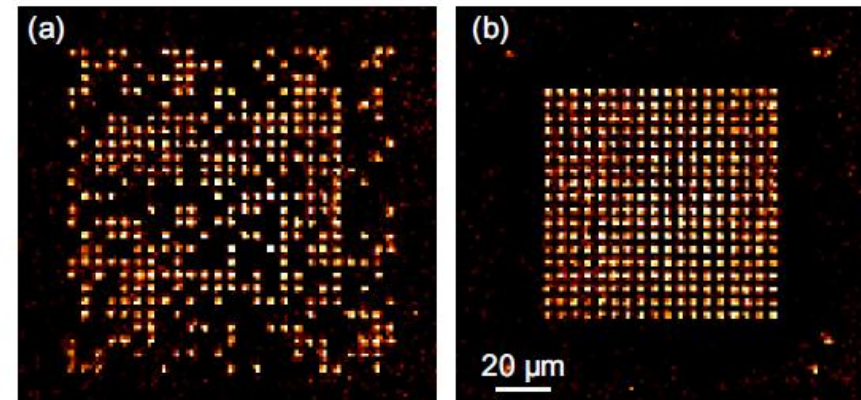


Cryogenic arrays: should be easy to go to large N !

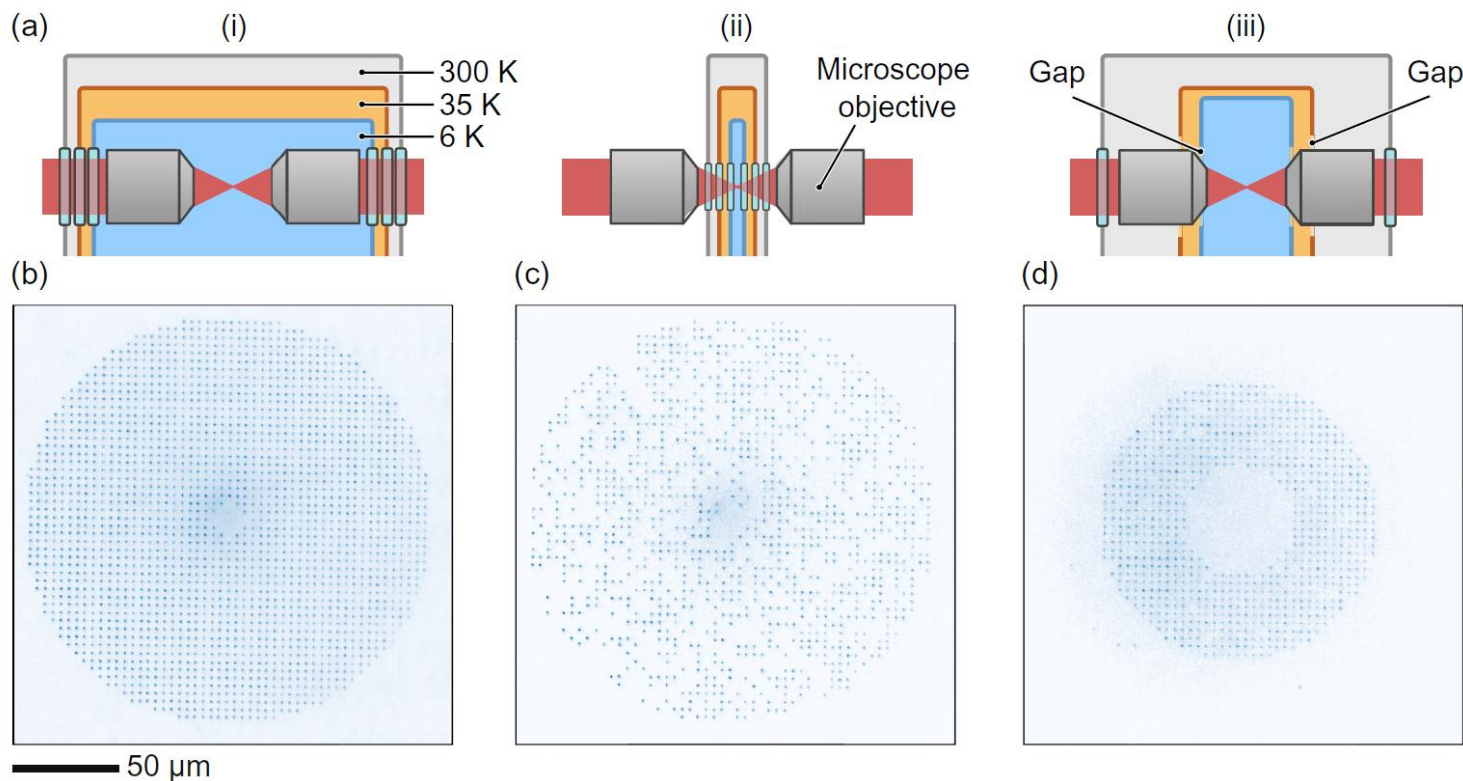
Schymik *et al.*, *Phys. Rev. A* **16**, 034013 (2022)

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

Go for microscope objectives!



Cryogenic arrays:

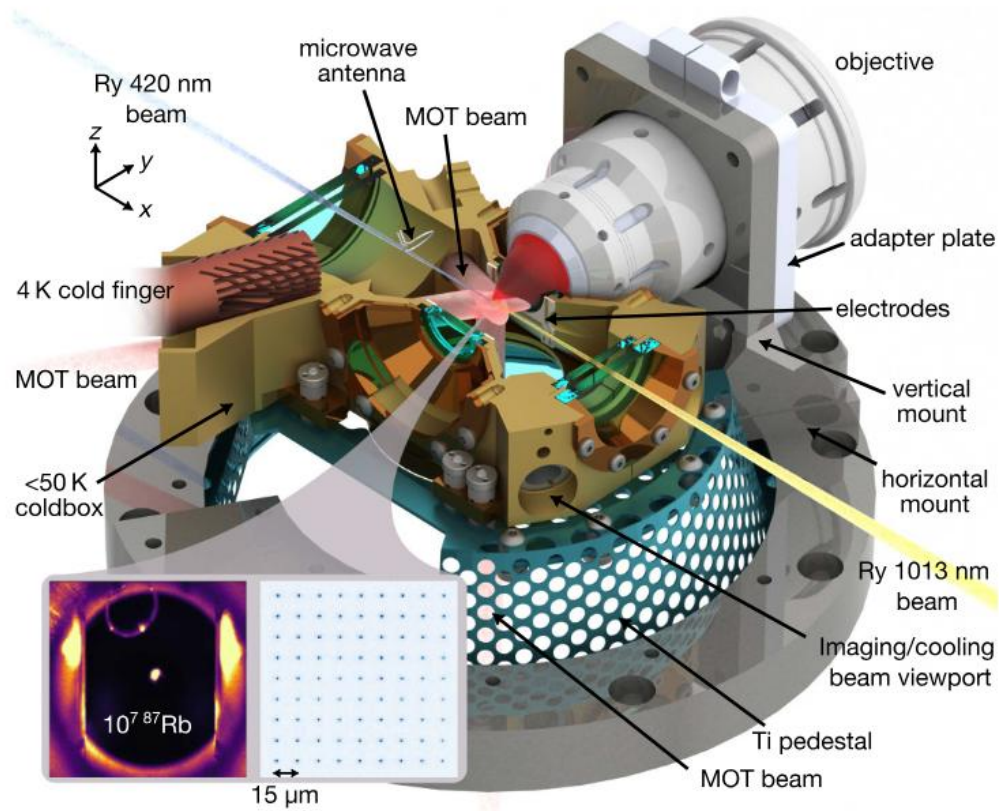


G. Pichard *et al.*,
Phys. Rev. Applied **22**, 024073 (2024)

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

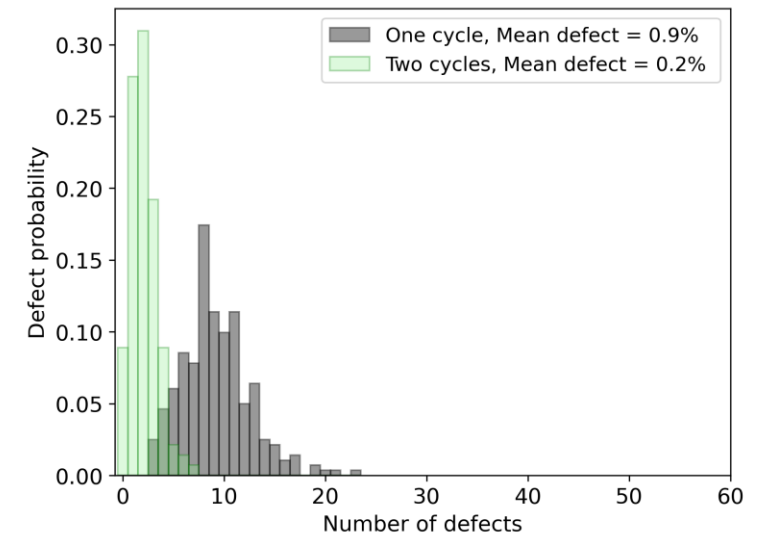
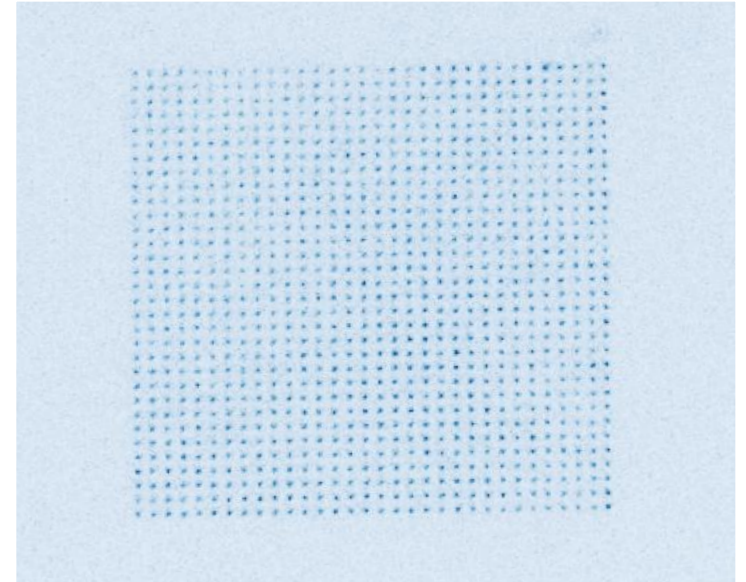
Cryogenic arrays:

D. Lim *et al.*, in preparation (2026)

Microscope objectives + windows in 30K shield

Lifetime ~ 5000 s

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



Lecture 2

1. Rydberg atoms

2. Interactions between Rydberg atoms

3. Van der Waals interactions and Rydberg blockade

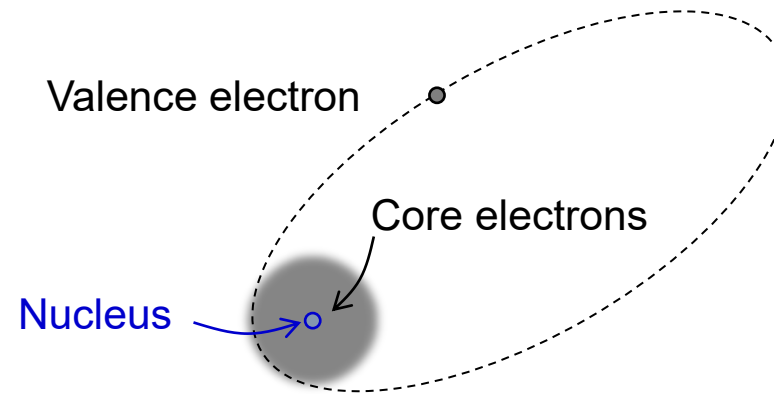
4. Resonant dipole-dipole interactions

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 mathematical formula on aged paper, showing the Rydberg formula for the wavelength of light emitted in the transition of an electron between two energy levels:

$$\frac{1}{\lambda} = R \left(\frac{1}{(n_1 + c_1)^2} - \frac{1}{(n_2 + c_2)^2} \right)$$

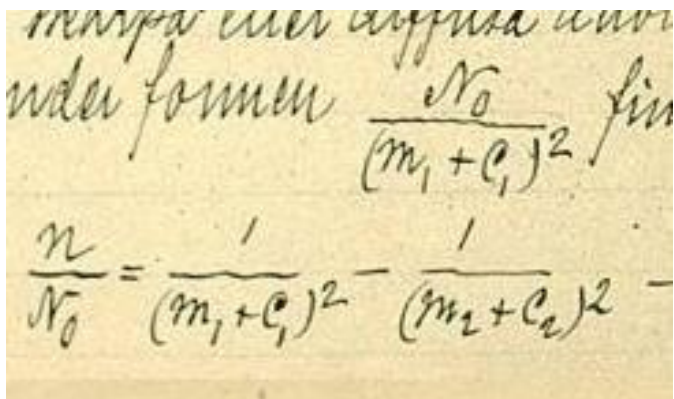
Three “golden ages” of Rydberg atoms

Spectroscopy & Early QM

Tunable lasers: atom-light interaction

1890

Rydberg
Bohr
Fermi
Segrè...

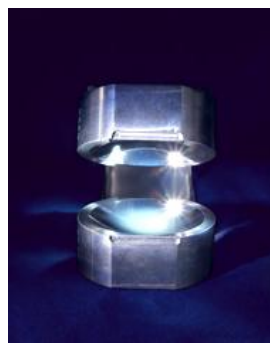


Handwritten manuscript snippet showing the Rydberg formula:

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

~1975

Kleppner
Gallagher
Walther
Haroche...



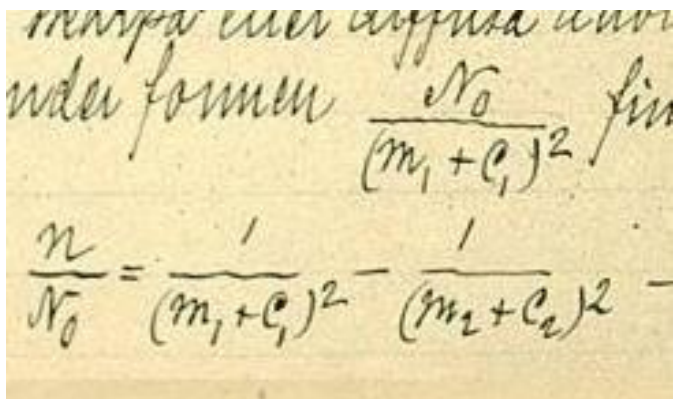
Three “golden ages” of Rydberg atoms

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1890

Rydberg
Bohr
Fermi
Segrè...

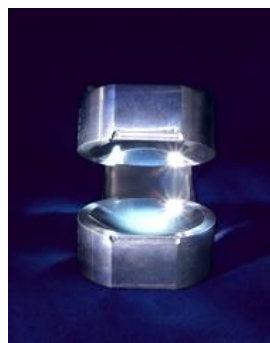


Handwritten manuscript snippet showing the Rydberg formula:

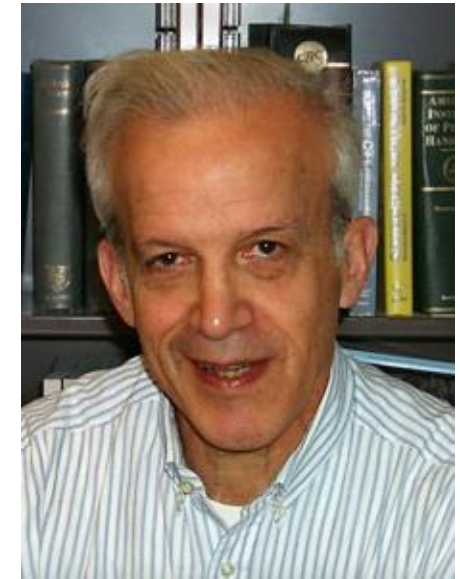
$$\frac{n}{N_0} = \frac{1}{(m_1 + c_1)^2} - \frac{1}{(m_2 + c_2)^2}$$

~1975

Kleppner
Gallagher
Walther
Haroche...



Dan Kleppner (1932-2025)



PHYSICAL REVIEW A

VOLUME 20, NUMBER 6

DECEMBER 1979

Stark structure of the Rydberg states of alkali-metal atoms

Myron L. Zimmerman, Michael G. Littman, Michael M. Kash, and Daniel Kleppner

Research Laboratory of Electronics and Department of Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

(Received 21 May 1979)

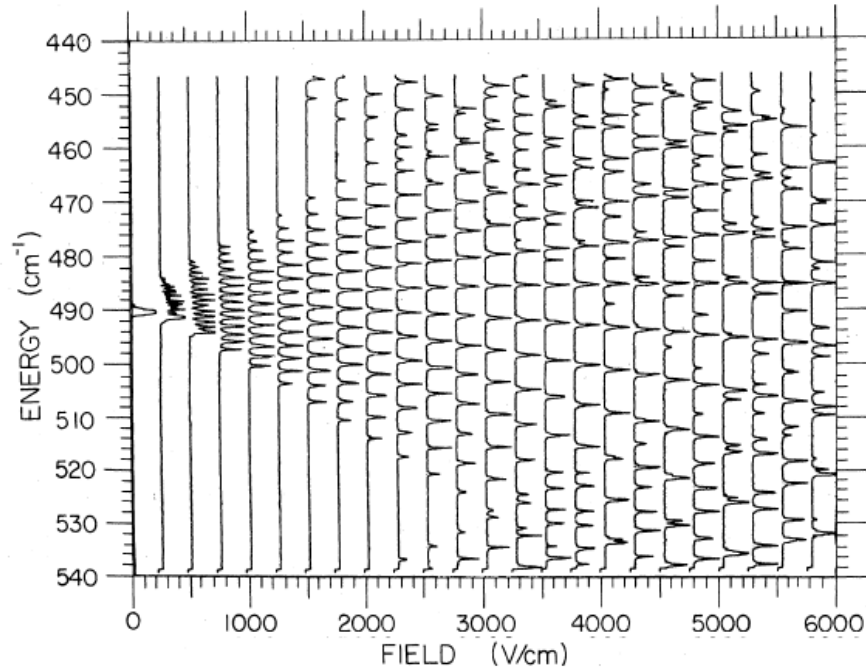


FIG. 4. Lithium, $|m|=1$; experimental Stark structure.

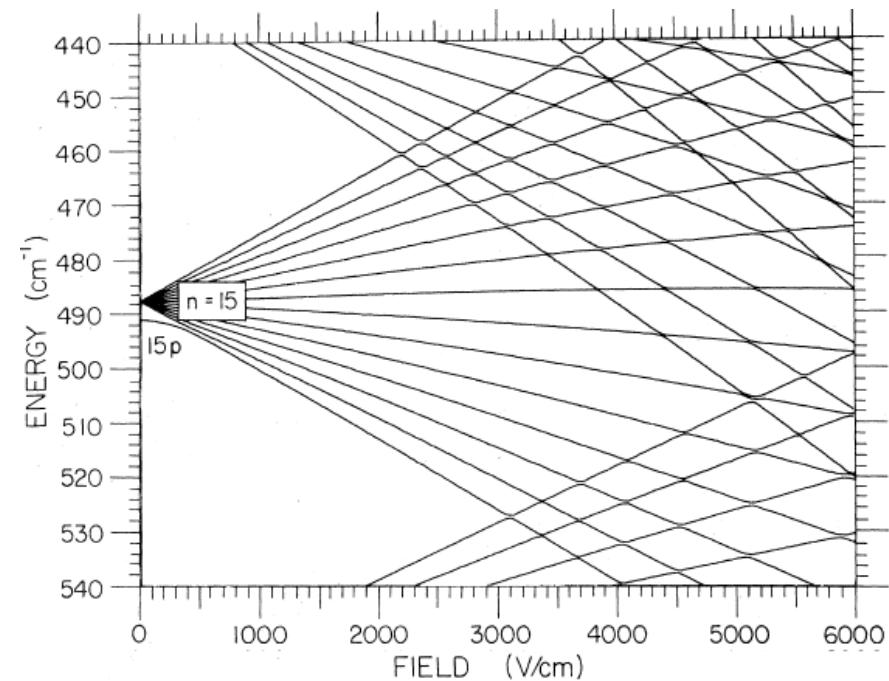


FIG. 3. Lithium, $|m|=1$.

Our life is easier now...

APPENDIX C. SOME COMPUTATIONAL CONSIDERATIONS

Our calculations were carried out on a PDP 11/34 minicomputer with floating-point hardware. The average instruction time is $3 \mu\text{sec}$ and the "multiply" instruction time is $13 \mu\text{sec}$. The time to calculate a single matrix element varies from 0.7 sec for $\langle 10, 9 | r | 10, 8 \rangle$ to 1.3 sec for $\langle 10, 0 | r | 10, 1 \rangle$. At $n=100, l=0$ the time is 2.1 sec. Approximately 11 min is required to calculate all matrix elements in the range $n=13-20$. The diagonalization time for this basis is approximately $t = 370 \text{ sec} \times [E(\text{kV/cm})]^{0.36}$. The time varies with the size of the basis set s roughly as s^2 . The total time to diagonalize all field points from 0 to 6 kV/cm in 100 V/cm steps is approximately 8 h.



APPENDIX B. DIAGONALIZATION PROCEDURE AND ERRORS

The energy matrices were diagonalized using the Jacobi diagonalization method adapted for digital computers by Von Neumann,²³ with a modified convergence test. Although faster and perhaps more accurate methods exist for this type of diagonalization, the Jacobi method had the advantage of requiring a minimum of computer memory.

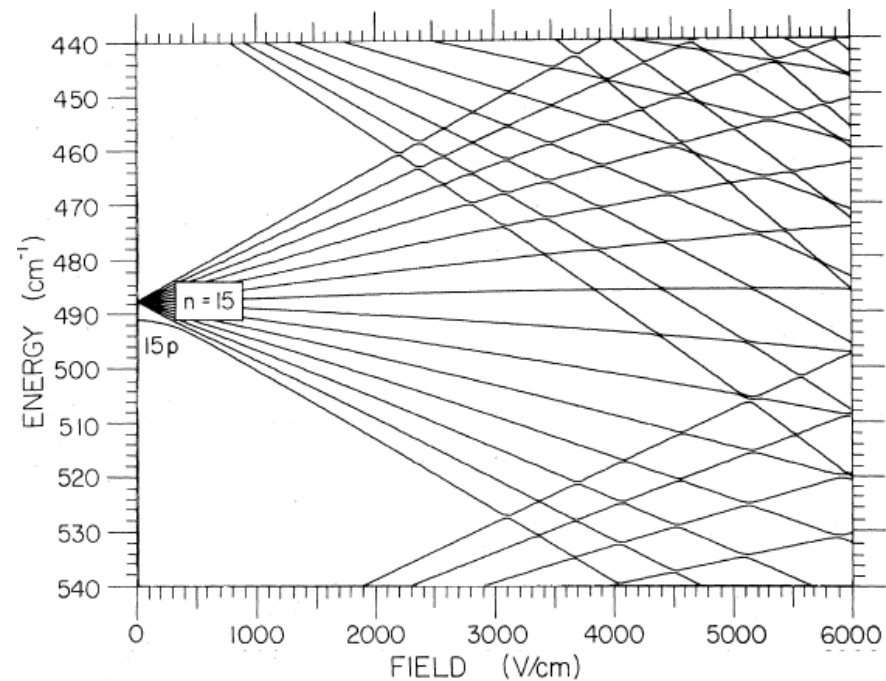


FIG. 3. Lithium, $|m|=1$.

Three “golden ages” of Rydberg atoms

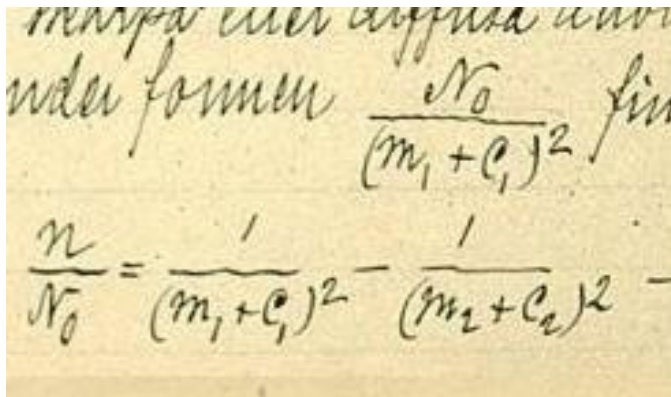
Spectroscopy & Early QM

Tunable lasers: atom-light interaction

Cold Rydberg atoms

1890

Rydberg
Bohr
Fermi
Segrè...

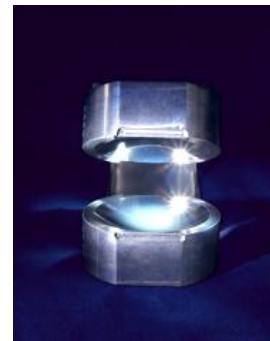


Handwritten manuscript snippet showing the Rydberg formula:

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

~1975

Kleppner
Gallagher
Walther
Haroche...

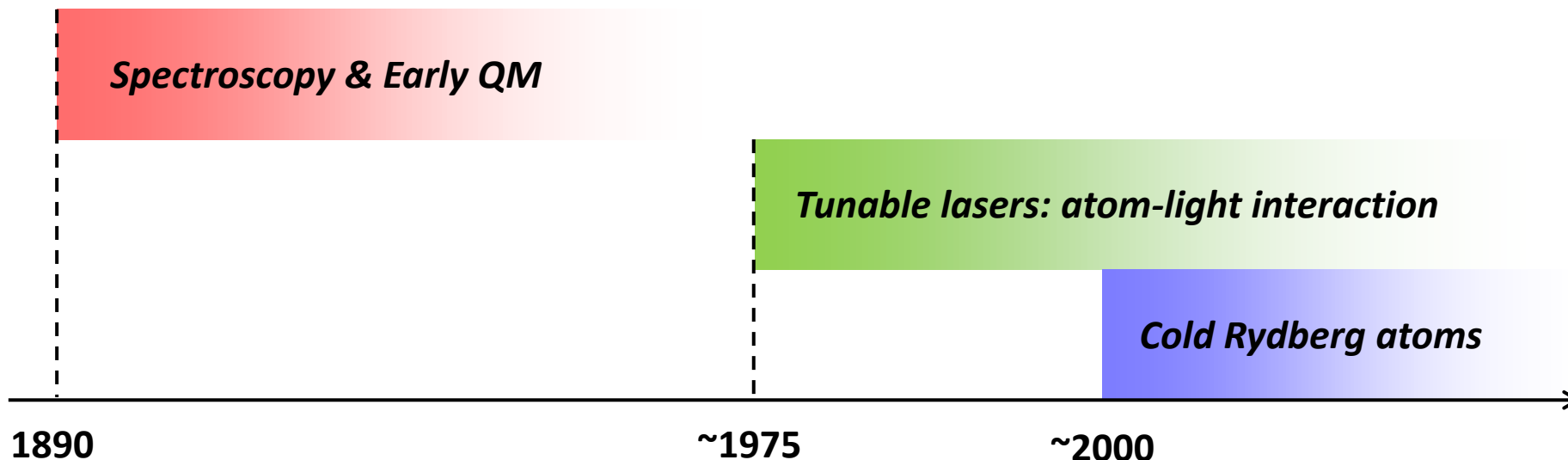


~2000

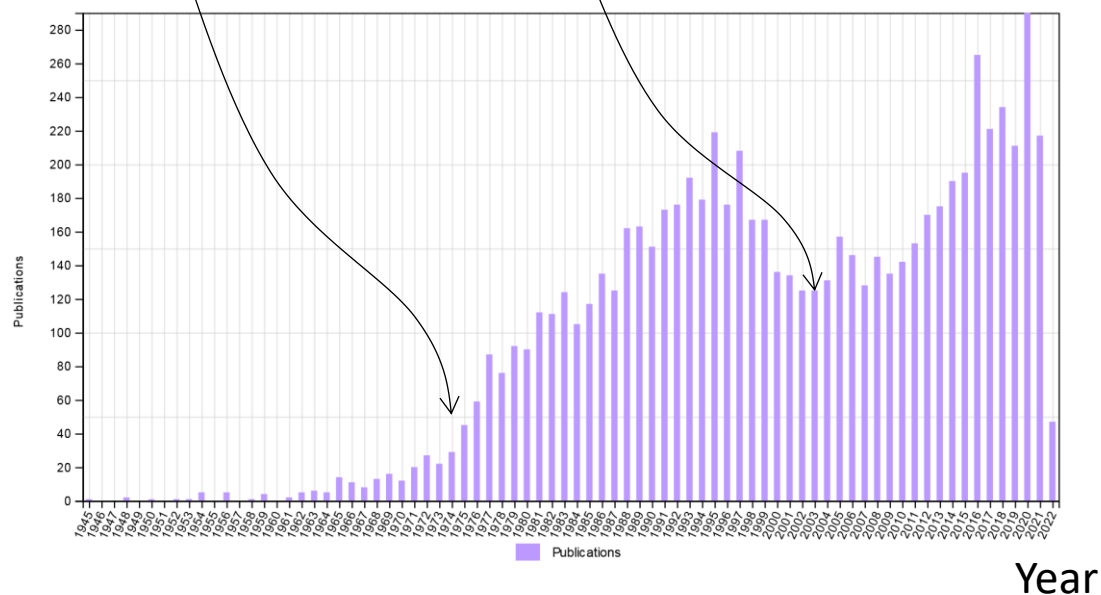
Gallagher
Pillet
Gould
Weidemüller
Pfau
Saffman
Grangier/Browaeys
Adams
Bloch...

And many others !

Three “golden ages” of Rydberg atoms



of citations per year of articles with the word “Rydberg” in the *title* (Web of Science)

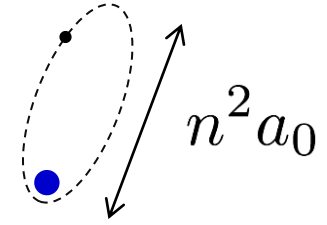


LECTURE 3

Wednesday, February 4th, 2025

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:

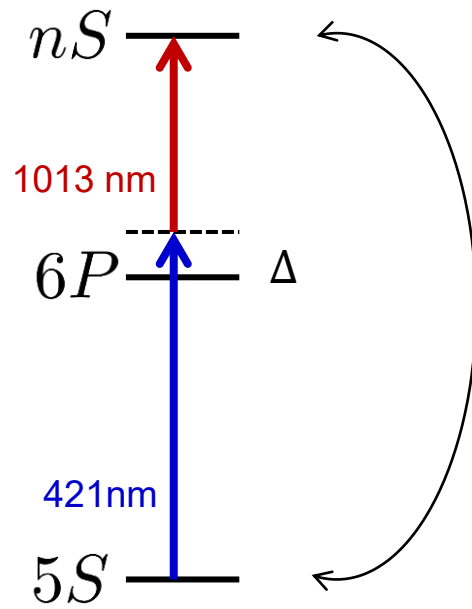
Electric dipole $\langle nS | d | nP \rangle \sim n^2$

Lifetime $\tau \sim n^3$ (hundreds of μs)

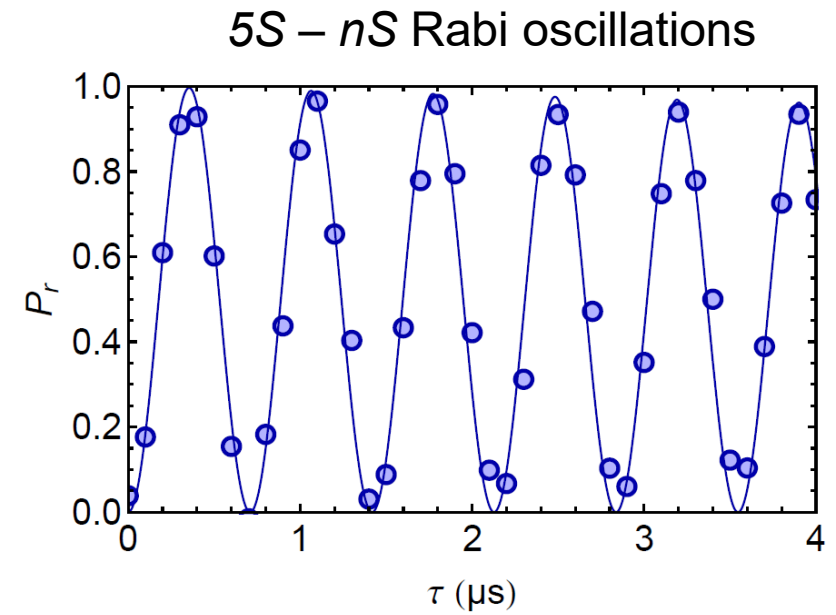
Polarizability $\alpha \sim n^7$

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

Rydberg excitation



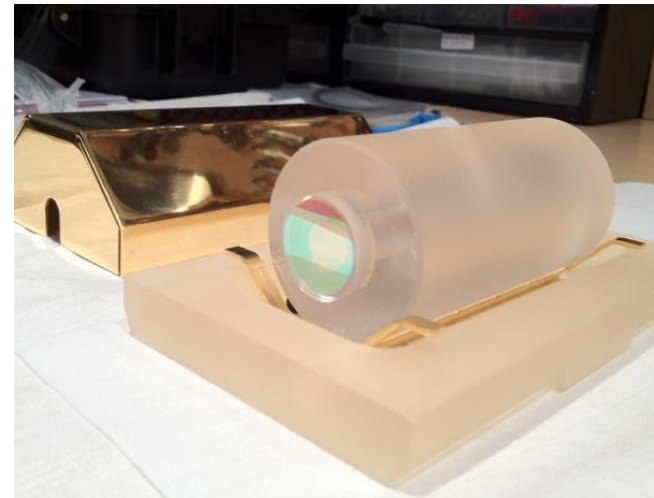
$$\Omega_{\text{eff}} = \frac{\Omega_1 \Omega_2}{2\Delta}$$



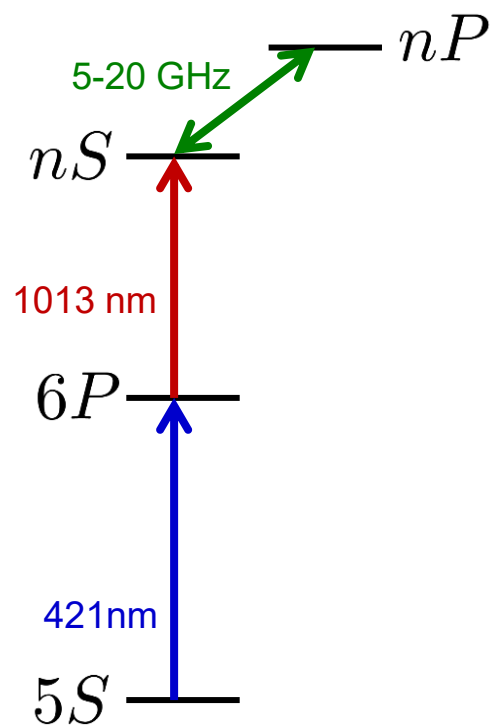
In practice



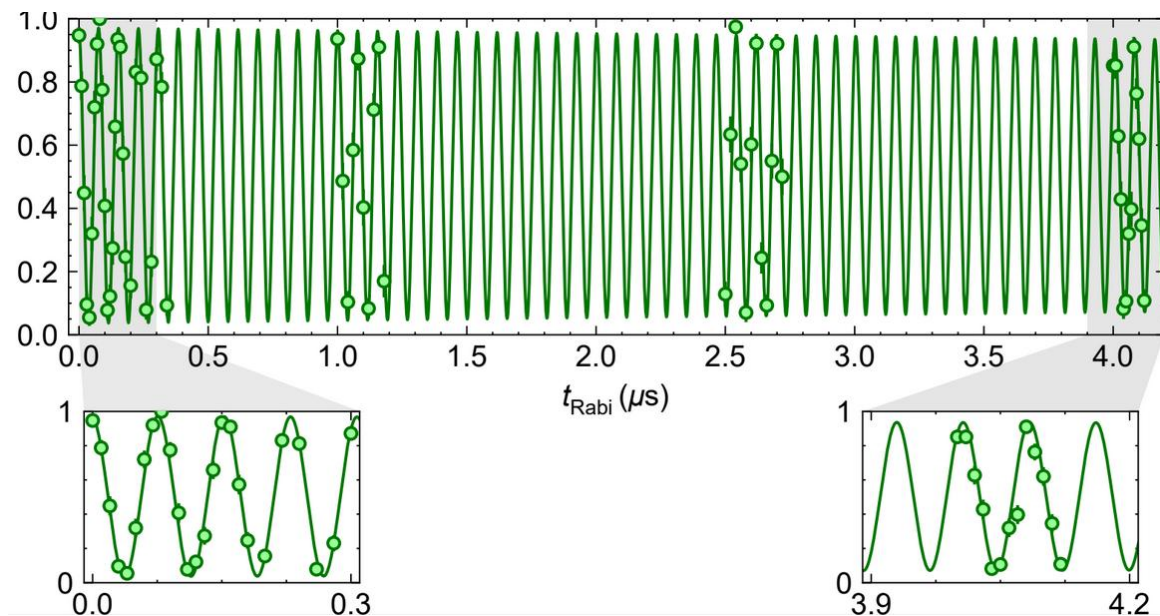
- Several watts on the atoms
- Frequency controlled to better than 10 kHz
- Low phase noise
- Ultra-stable cavity (finesse = 20 000, length fluctuations below 10^{-12} m)



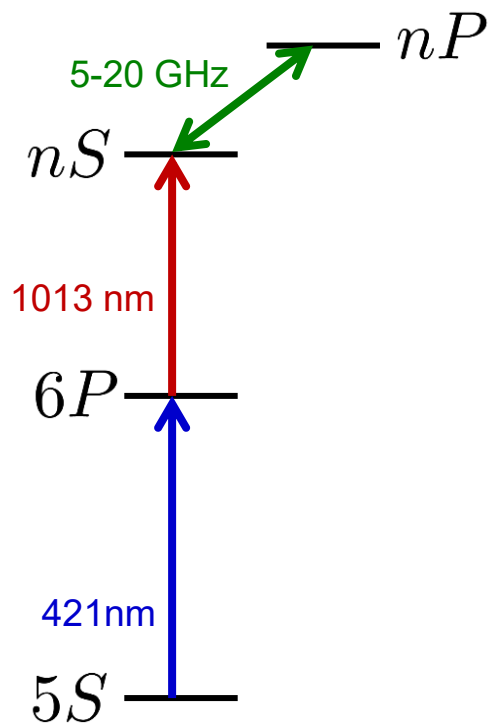
Rydberg excitation and microwave manipulations



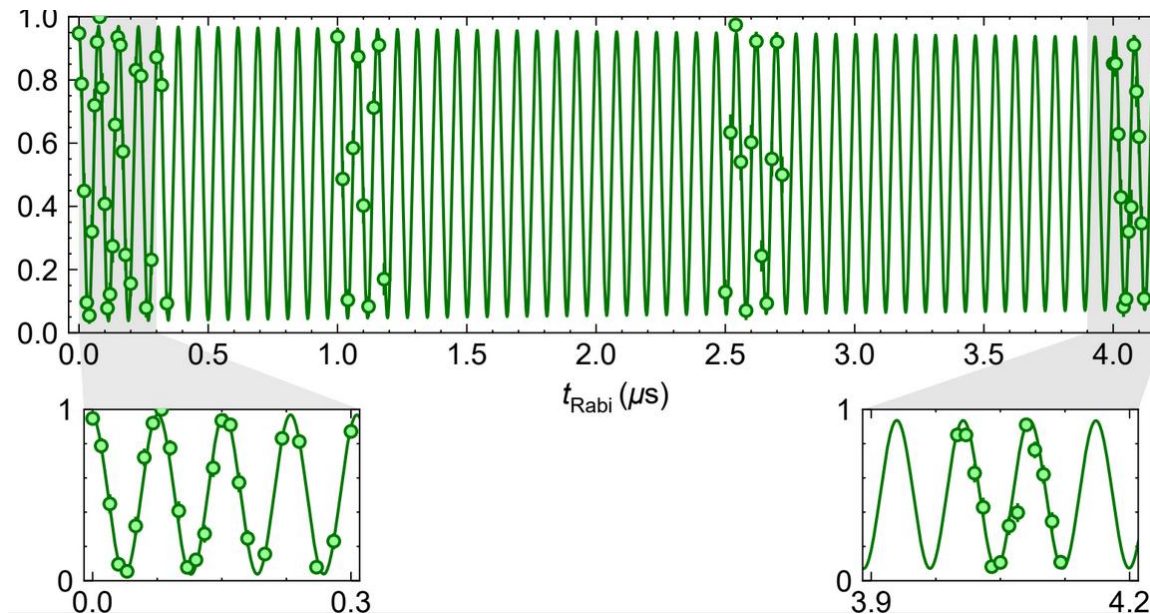
60S – 60P transition at 16.7 GHz



Rydberg excitation and microwave manipulations



60S – 60P transition at 16.7 GHz

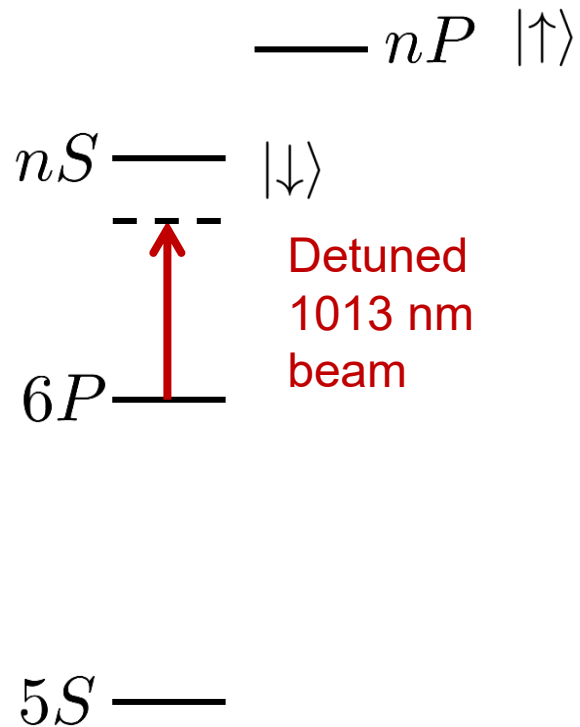


Optical addressing

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

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

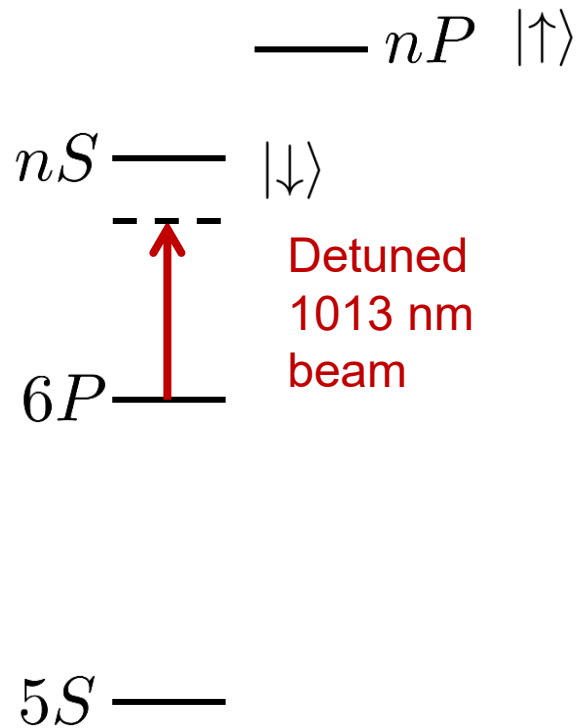
- First experiments with a *single beam*:
S. de Léséleuc *et al.*, [PRL **119**, 053202 \(2017\)](#)



Optical addressing

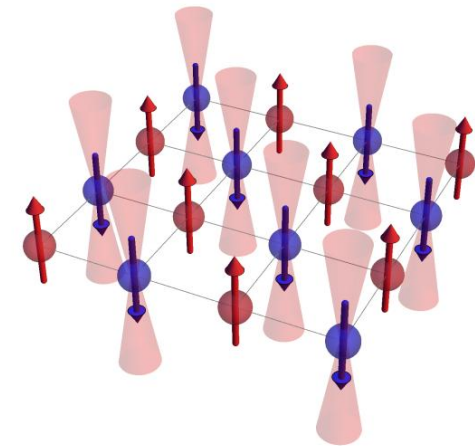
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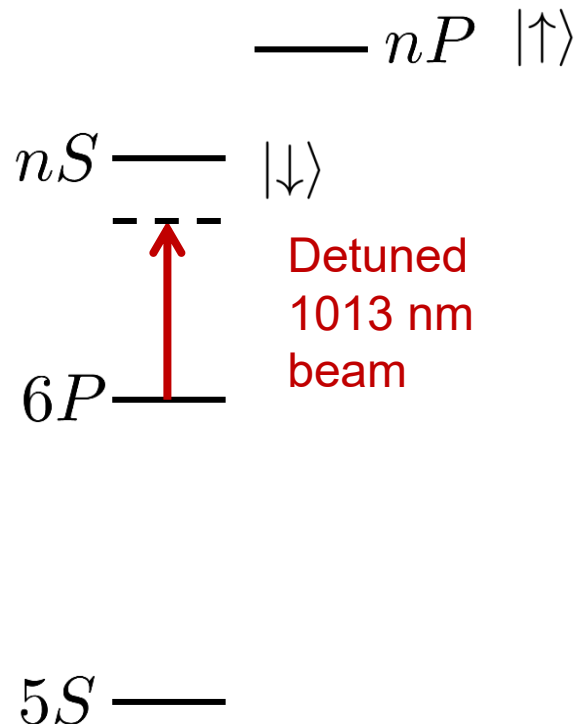
- Adding an SLM: spatial control
(but time dependence is global)



Optical addressing

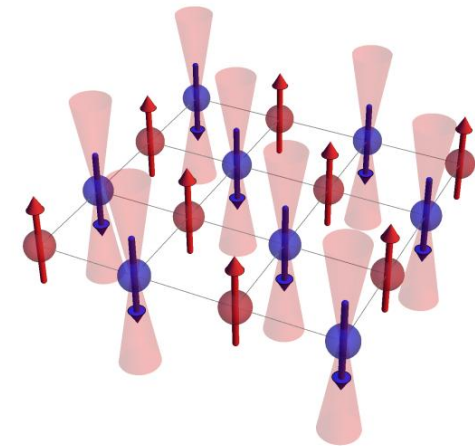
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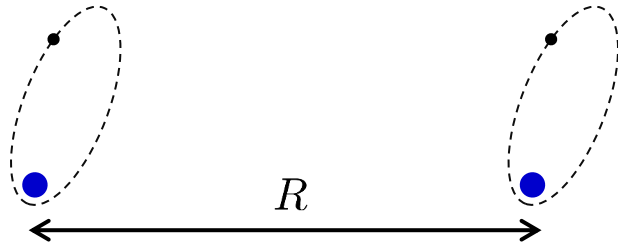
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S. de Léséleuc *et al.*, [PRL **119**, 053202 \(2017\)](#)

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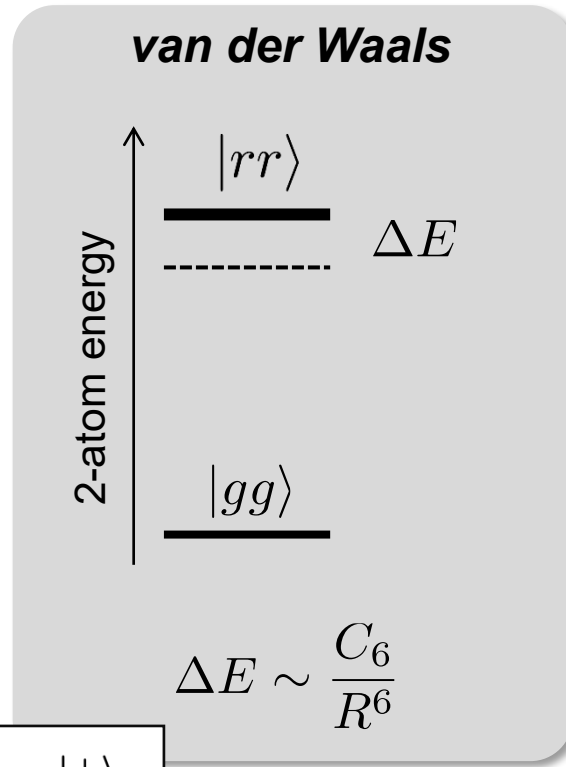


- Use several values of light-shift and multi-tone microwaves
G. Bornet *et al.*, [Phys. Rev. Lett. **132**, 263601 \(2024\)](#).

Interactions between Rydberg states



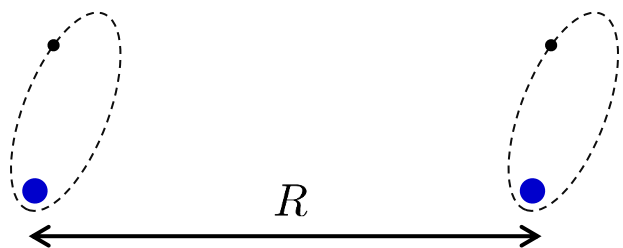
$$\hat{V}_{\text{ddi}} = \frac{1}{4\pi\epsilon_0} \frac{\hat{\mathbf{d}}_1 \cdot \hat{\mathbf{d}}_2 - 3(\hat{\mathbf{d}}_1 \cdot \hat{\mathbf{n}})(\hat{\mathbf{d}}_2 \cdot \hat{\mathbf{n}})}{R^3}$$



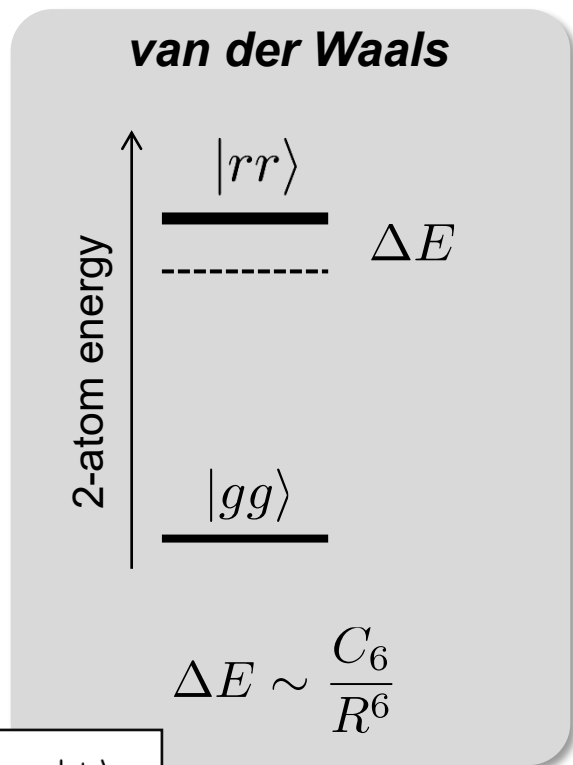
$$\begin{cases} |g\rangle \rightarrow |\downarrow\rangle \\ |r\rangle \rightarrow |\uparrow\rangle \end{cases}$$

Ising-like interaction

Interactions between Rydberg states

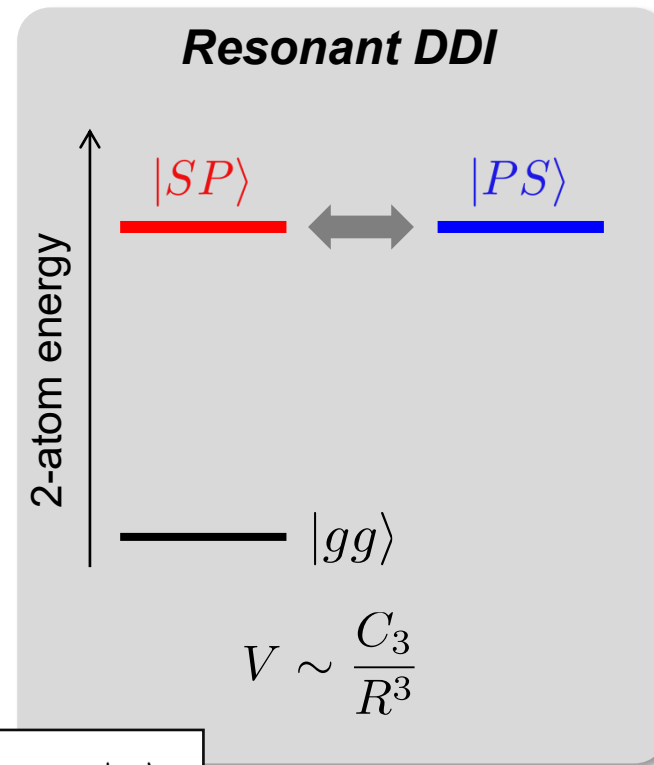


$$\hat{V}_{\text{ddi}} = \frac{1}{4\pi\epsilon_0} \frac{\hat{\mathbf{d}}_1 \cdot \hat{\mathbf{d}}_2 - 3(\hat{\mathbf{d}}_1 \cdot \hat{\mathbf{n}})(\hat{\mathbf{d}}_2 \cdot \hat{\mathbf{n}})}{R^3}$$



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Ising-like interaction



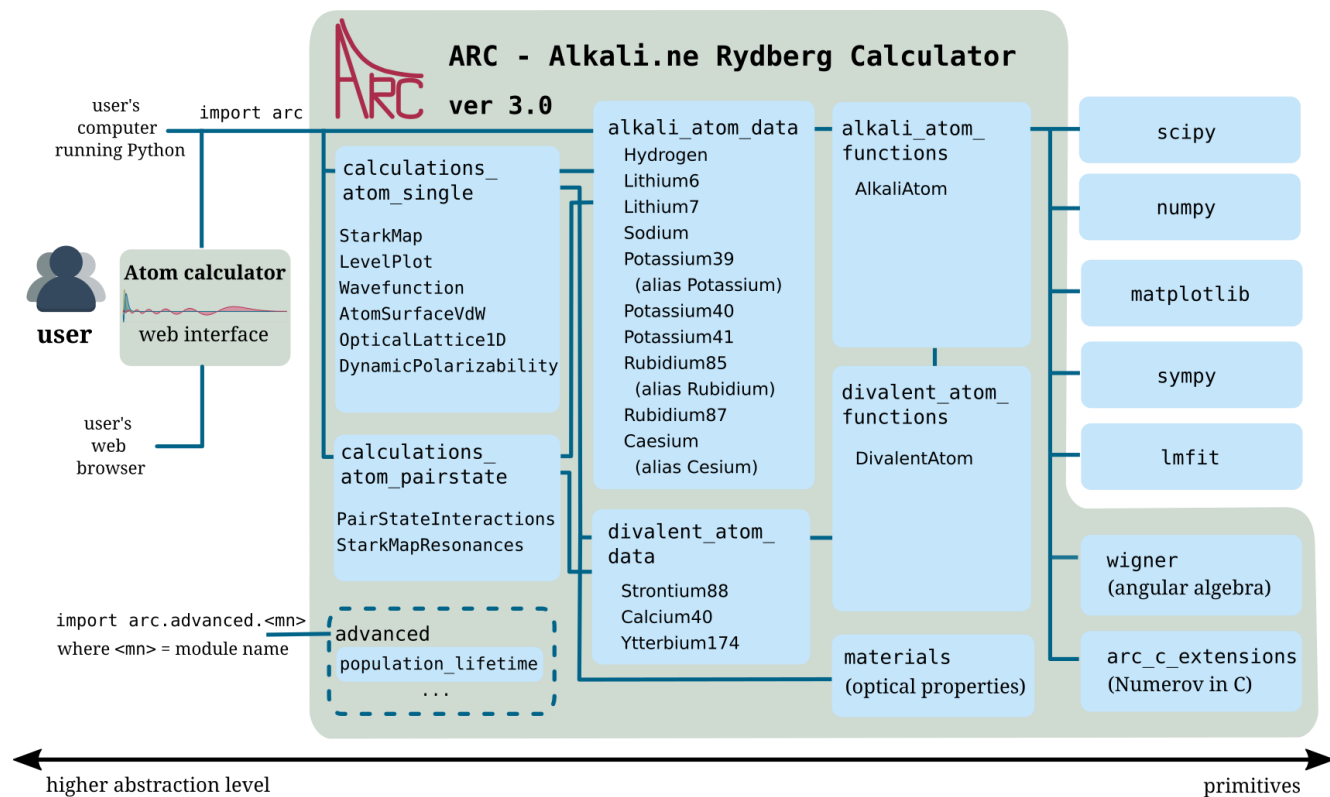
$$\begin{cases} |S\rangle \rightarrow |\downarrow\rangle \\ |P\rangle \rightarrow |\uparrow\rangle \end{cases}$$

XY interaction (flip-flop)

Python packages to calculate interactions

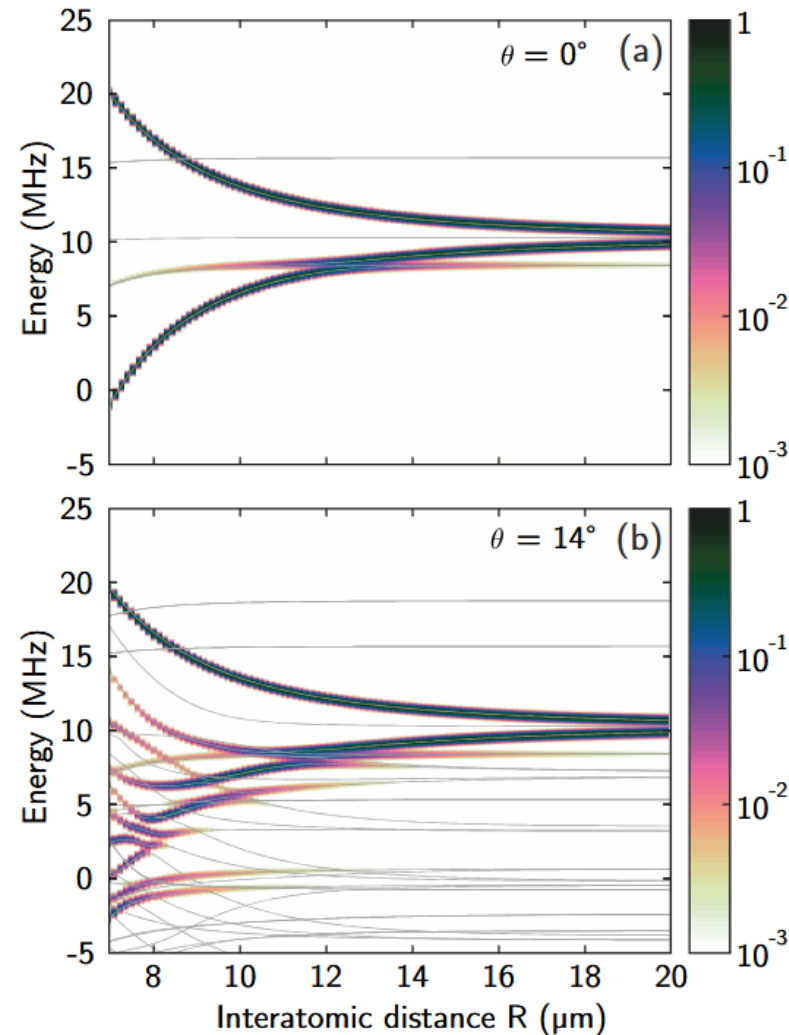
ARC

Nikola Sibalic *et al*, Durham



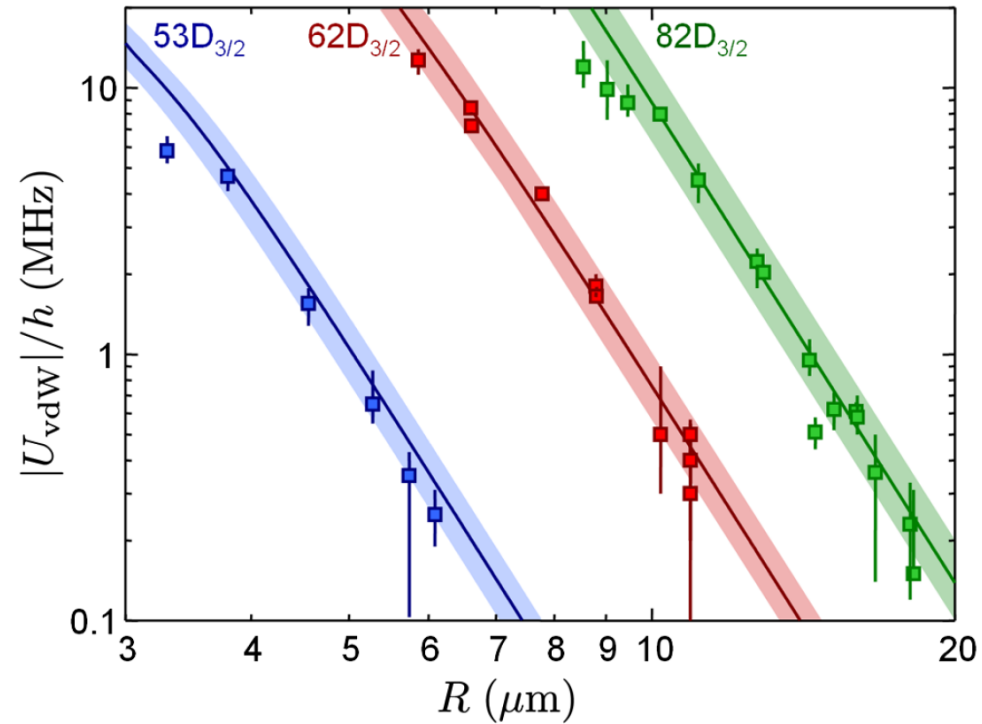
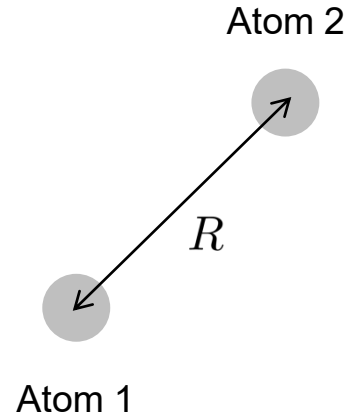
Pair Interactions

Sebastian Weber *et al*, Stuttgart



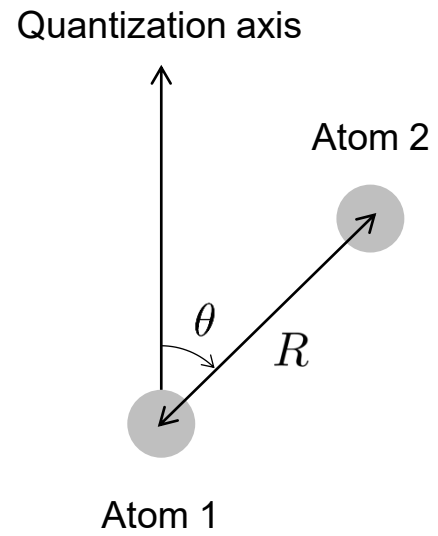
Measuring the van der Waals interaction

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

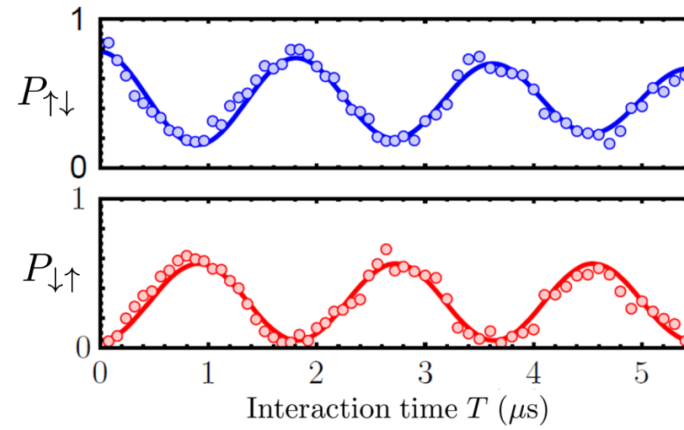


No adjustable parameter!

Measuring the resonant DDI



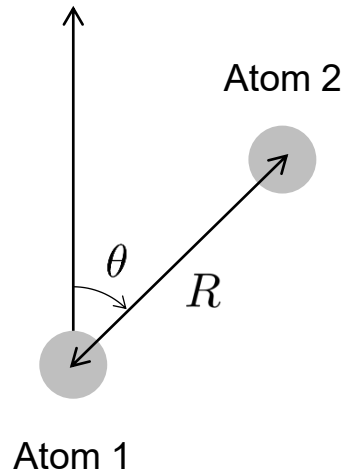
- **Prepare $|\uparrow\downarrow\rangle$ and let the two atoms evolve**



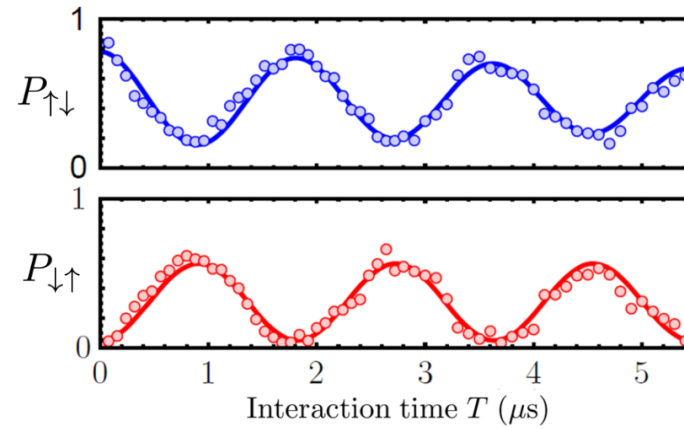
Coherent flip-flops
over $R = 30 \mu\text{m}$!

Measuring the resonant DDI

Quantization axis

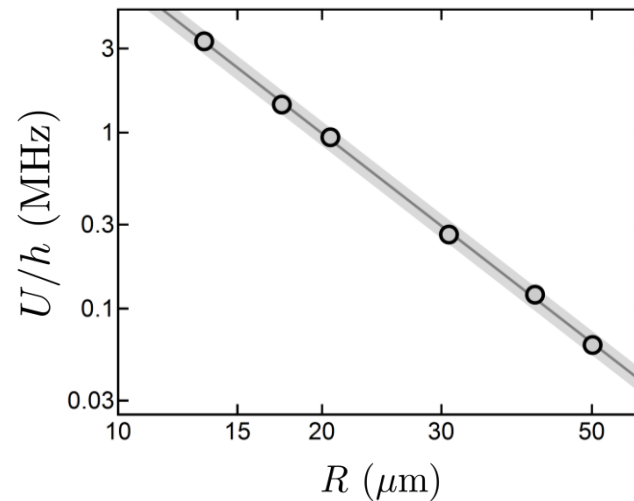


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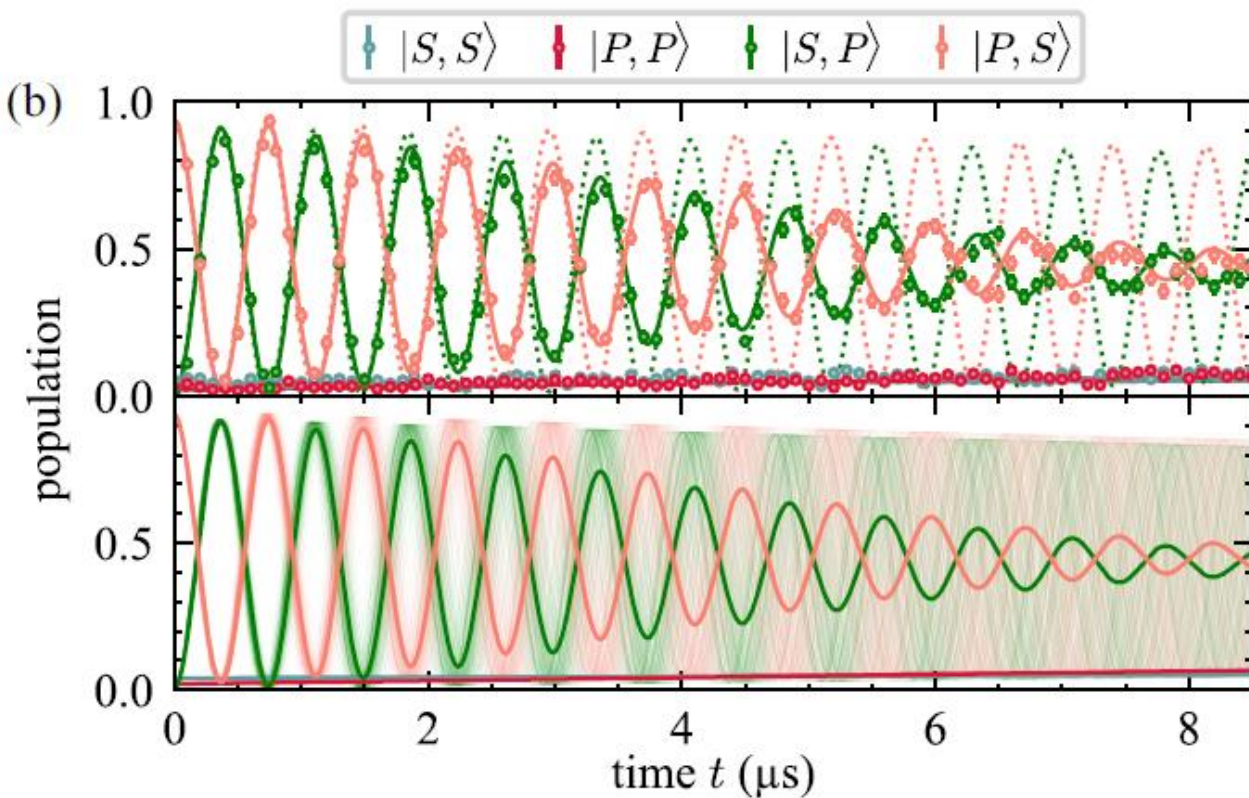
Coherent flip-flops
over $R = 30 \mu\text{m}$!

- **Vary the distance**



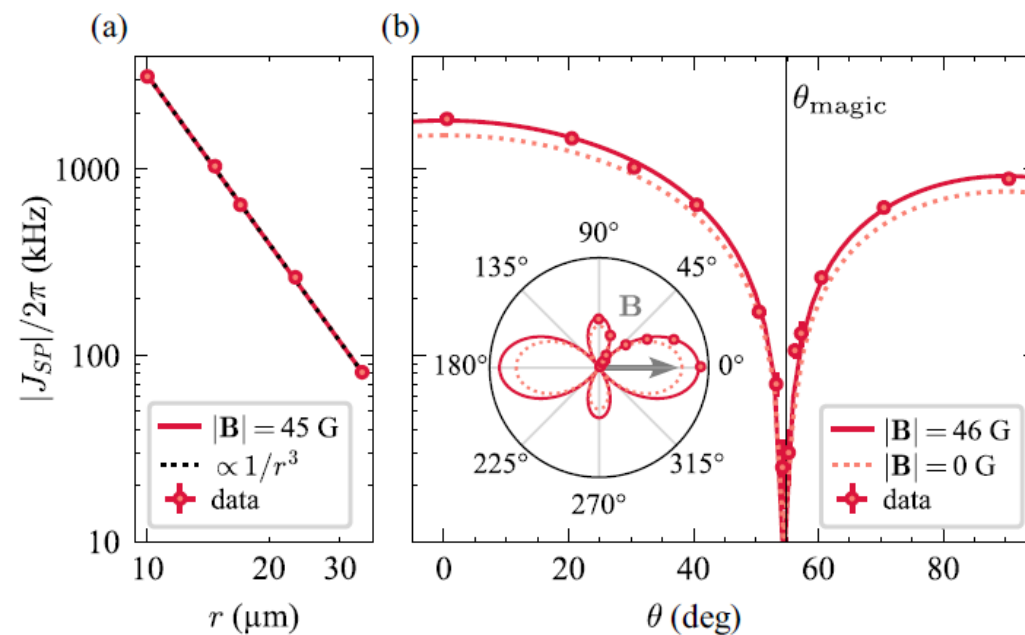
$1/R^3$ interaction

Measuring the resonant DDI, ten years later

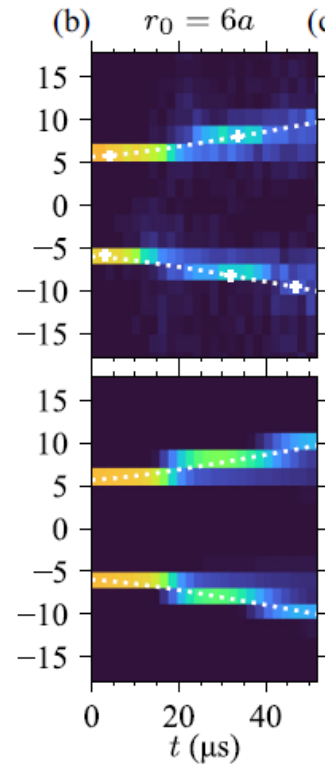
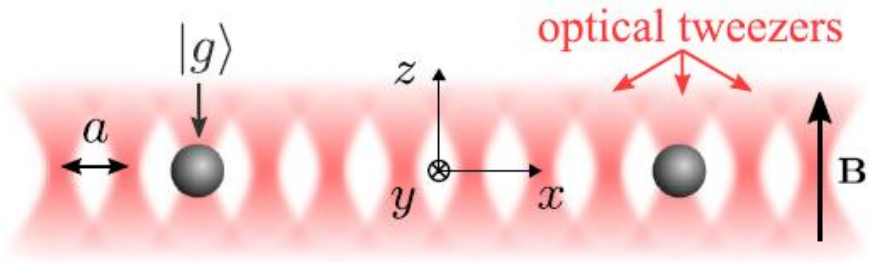


Angular dependence

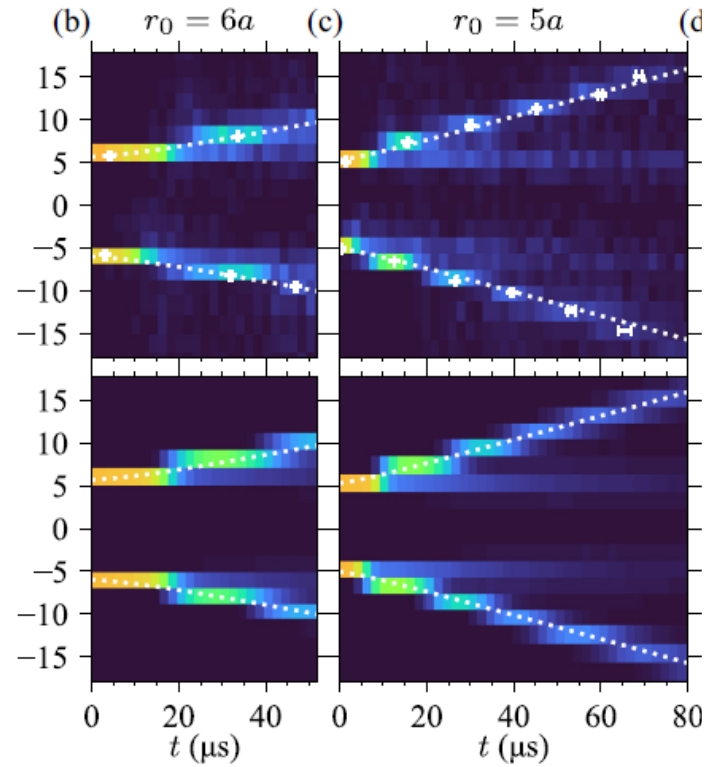
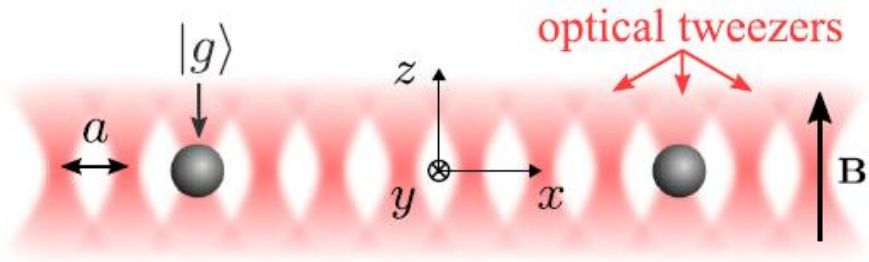
$$V_{\text{dd}} \propto 1 - 3 \cos^2 \theta$$



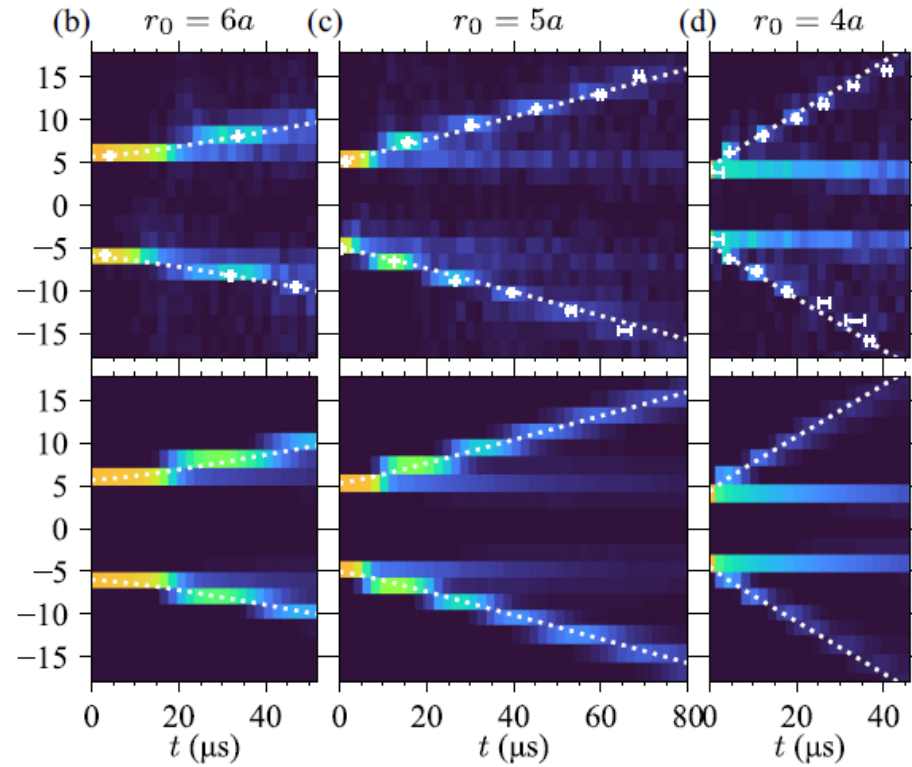
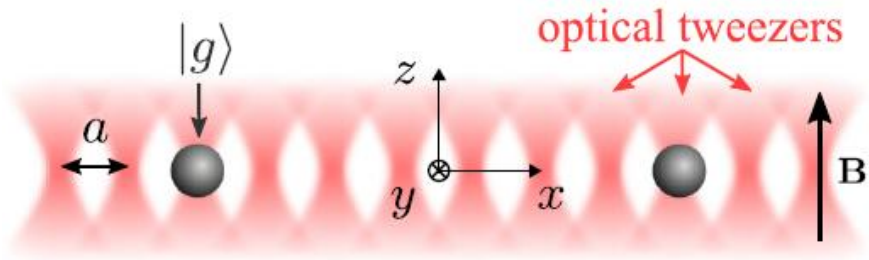
Playing with the interactions: mechanical effects of the vdW interaction



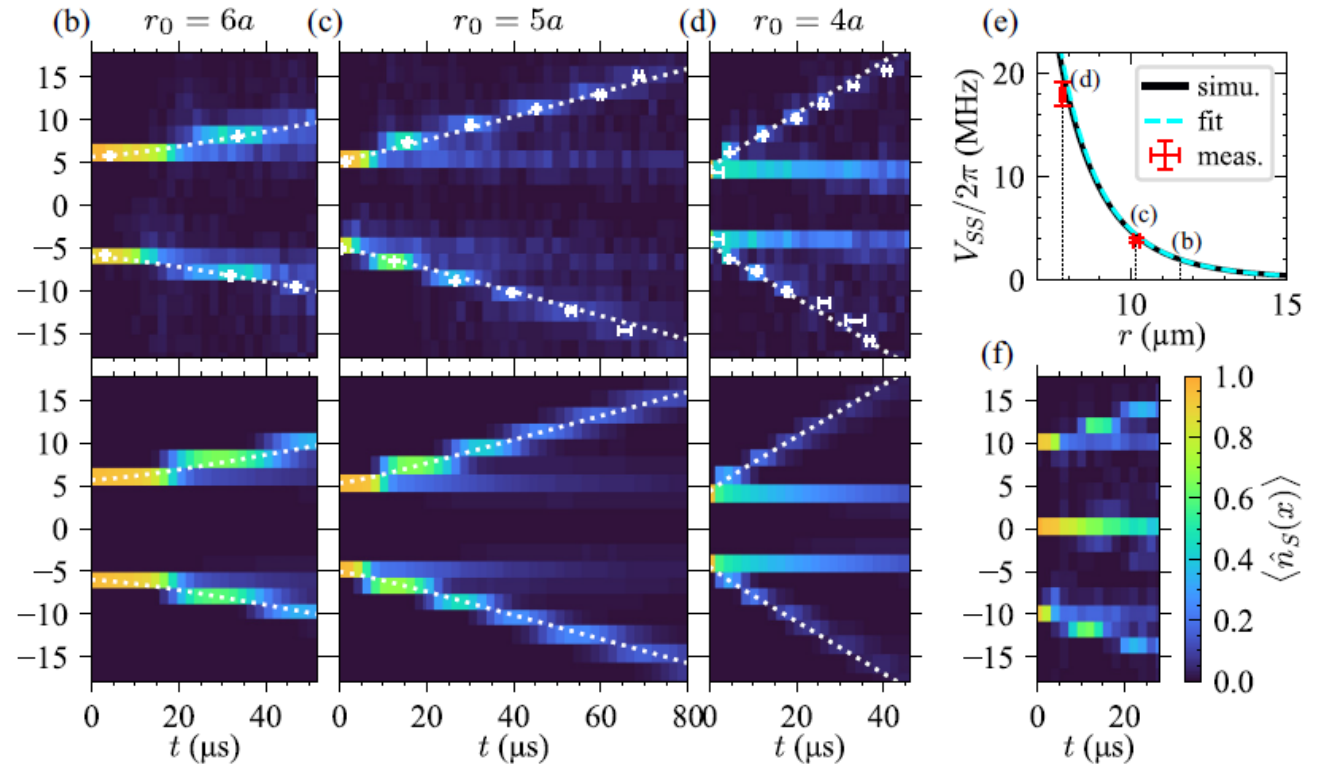
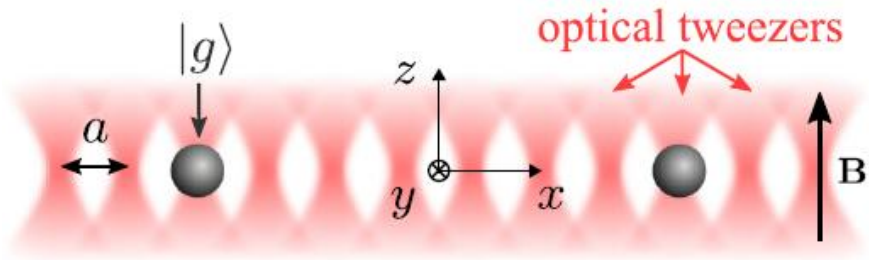
Playing with the interactions: mechanical effects of the vdW interaction



Playing with the interactions: mechanical effects of the vdW interaction



Playing with the interactions: mechanical effects of the vdW interaction



Quantum simulation, at last!

1. Qu. sim. of the Ising model

2. Qu. sim. of the XY model

3. Qu. sim. of the $t - J$ model

The transverse-field Ising model

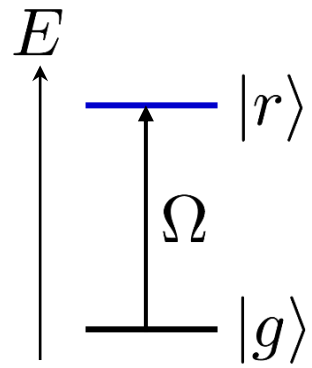
P. Scholl *et al.*, *Nature* **595**, 233 (2021)



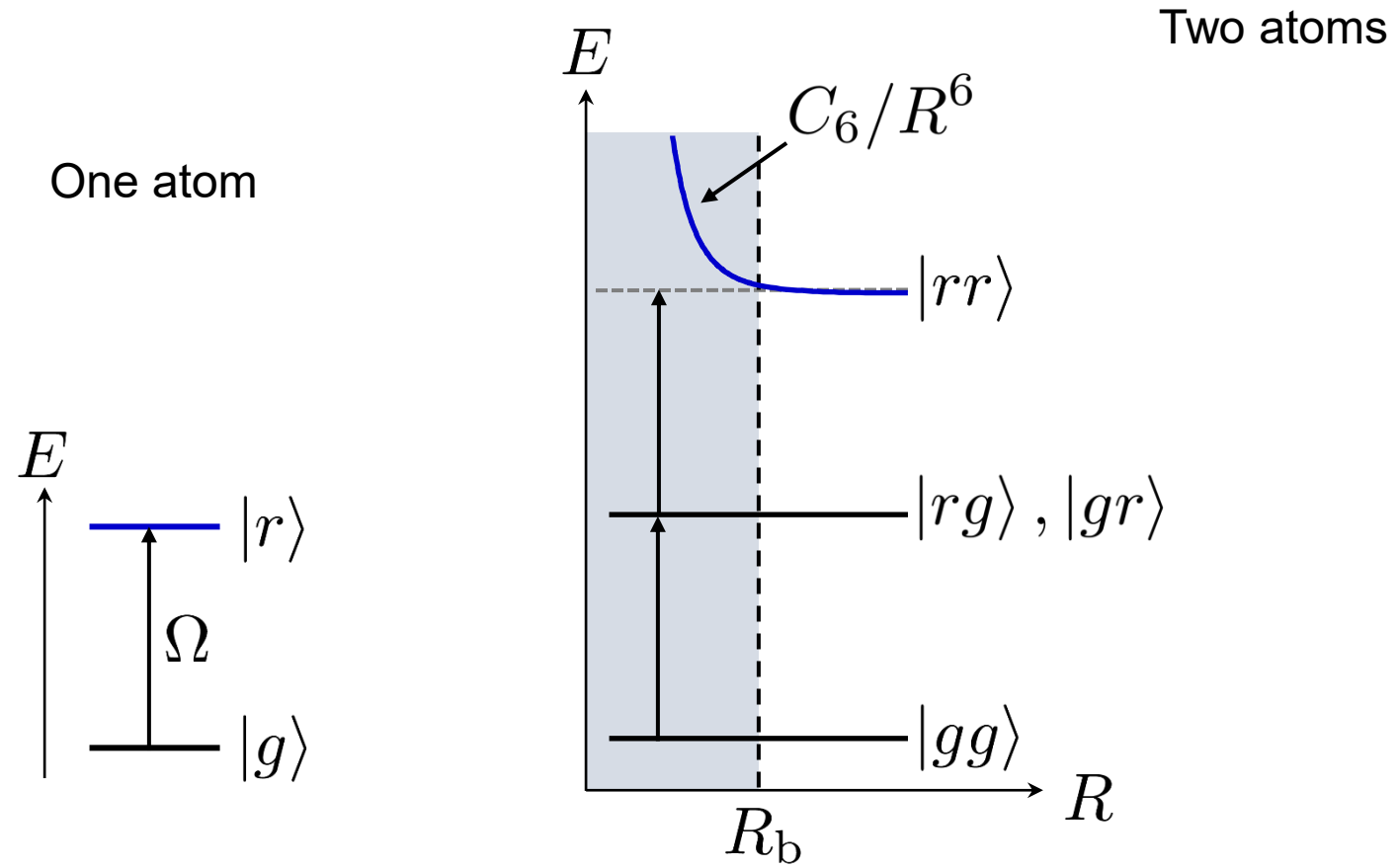
Andreas Läuchli
(Innsbruck, now at PSI & EPFL)

Rydberg blockade

One atom

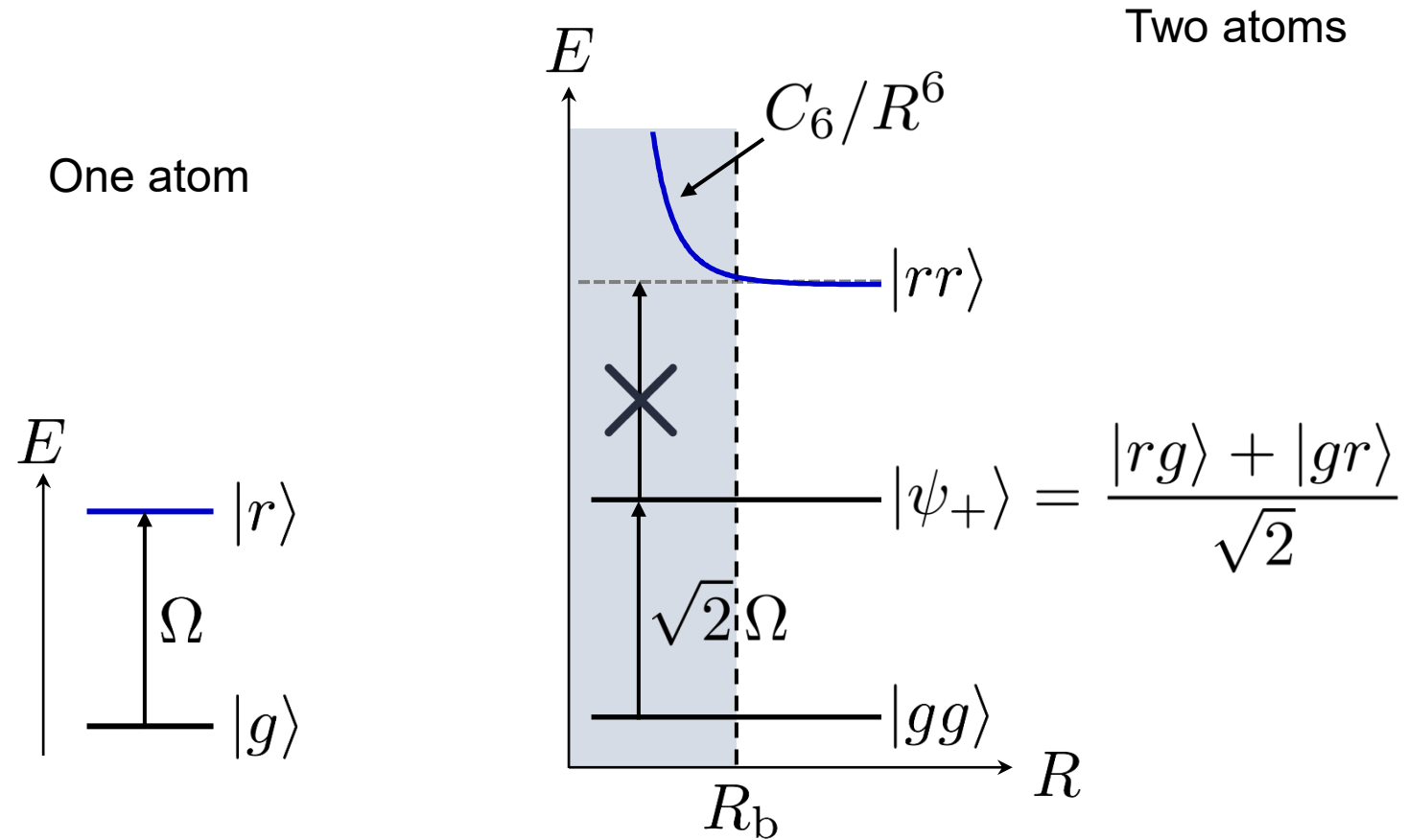


Rydberg blockade



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

Rydberg blockade

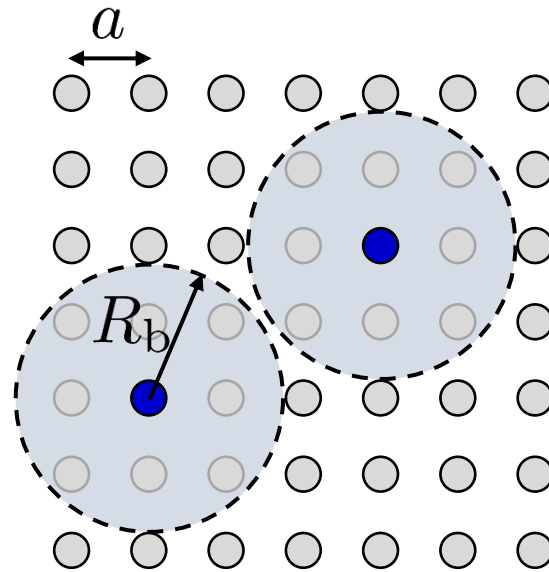


- Generate entanglement
- Basis of two-qubit gates
- Extends to N atoms in a blockade volume

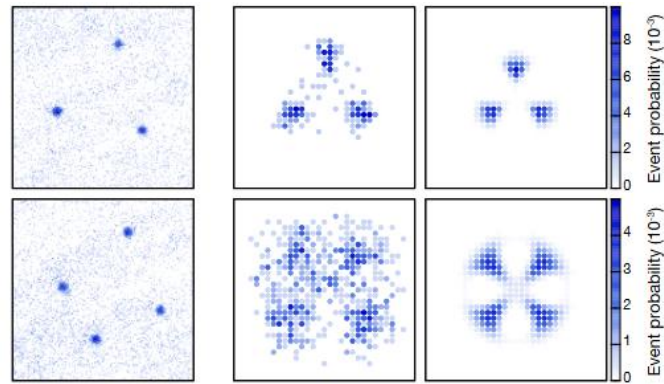
Rydberg blockade

Several blockade volumes in the array:

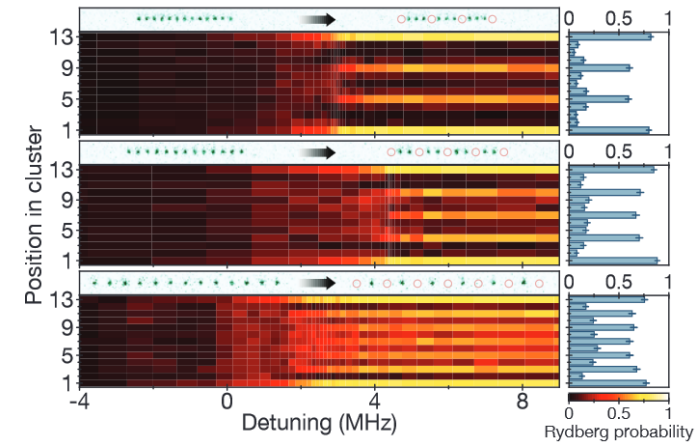
Strongly correlated quantum many-body systems!



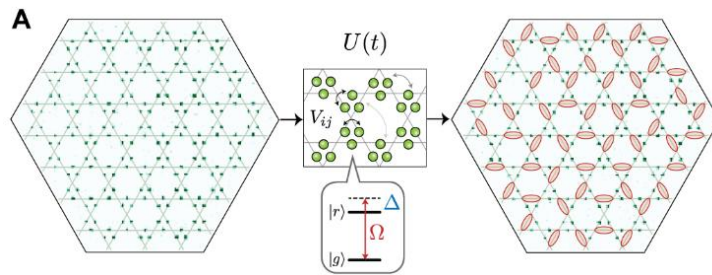
Many experiments on the Ising model



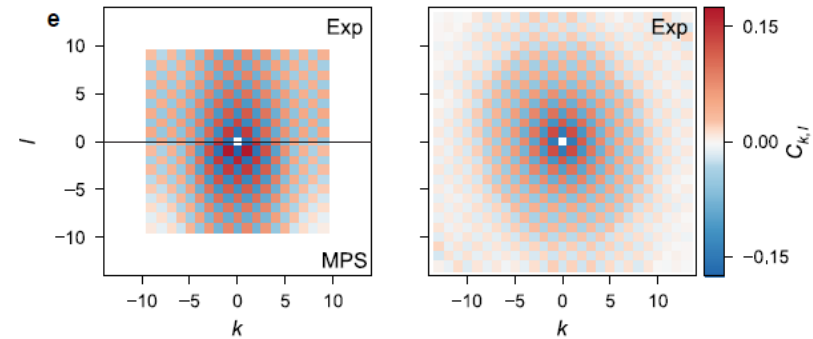
P. Schauss *et al.*, *Nature* **491**, 87 (2012)



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



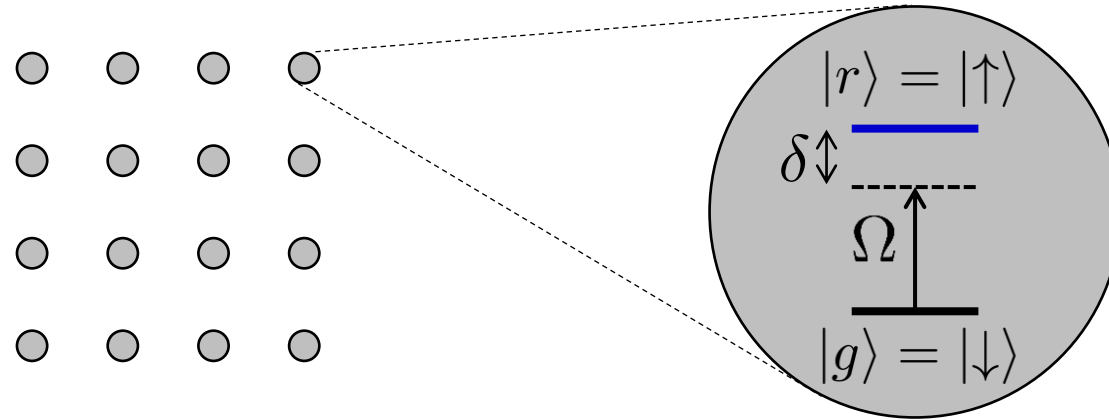
G. Semeghini *et al.*, *Science* **374**, 1242 (2021)



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

And many, many more examples!

Blockade: quantum Ising model



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

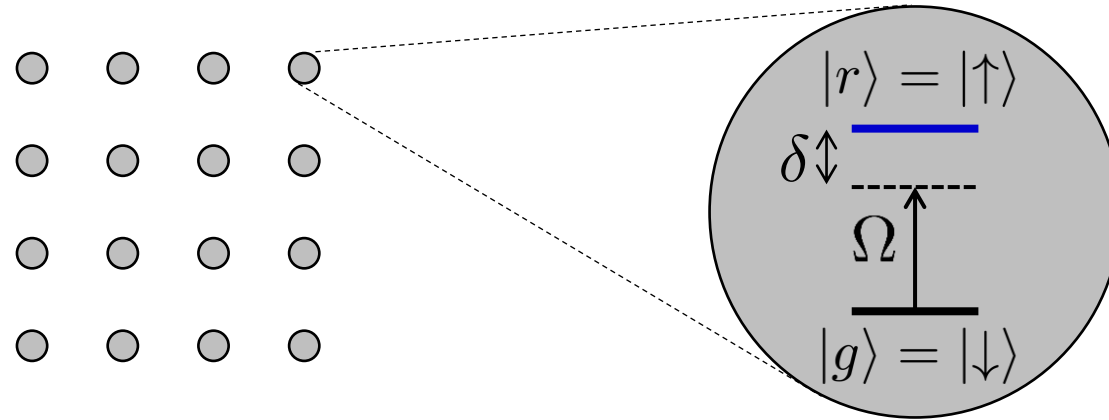
$$H = \sum_i \left(\frac{\hbar\Omega}{2} \sigma_x^i - \hbar\delta n^i \right) + \sum_{i<j} \frac{C_6}{R_{ij}^6} n_i n_j$$

Rabi frequency

Laser detuning

van der Waals interactions

Blockade: quantum Ising model



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

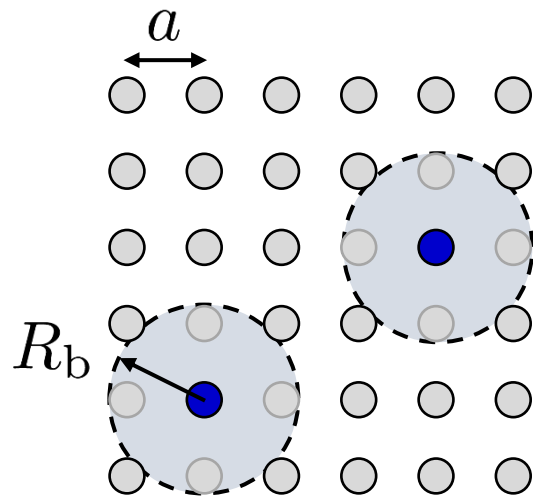
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Transverse B Longitudinal B Ising couplings

Ising model: adiabatic preparation

$$R_b = 1.2a$$

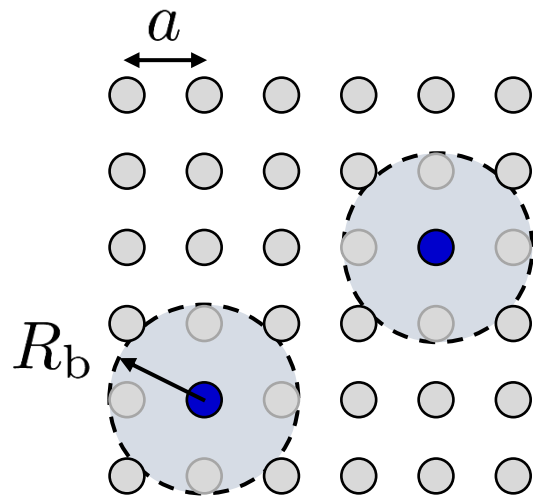
Nearest-neighbor blockade



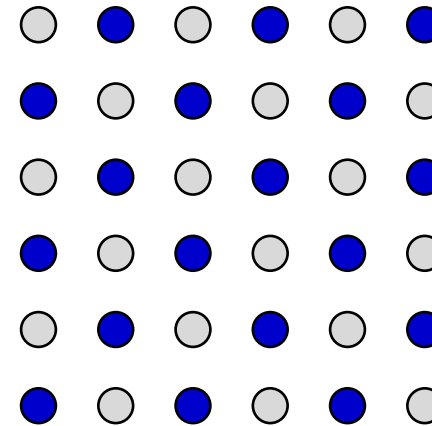
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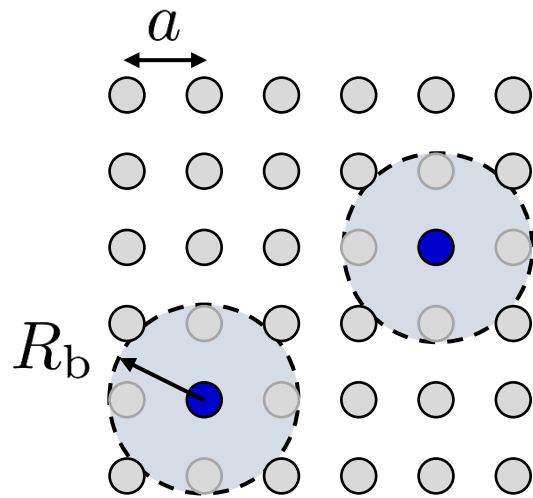
Antiferromagnetic ground state



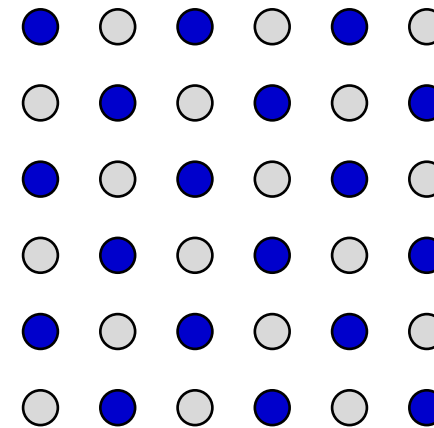
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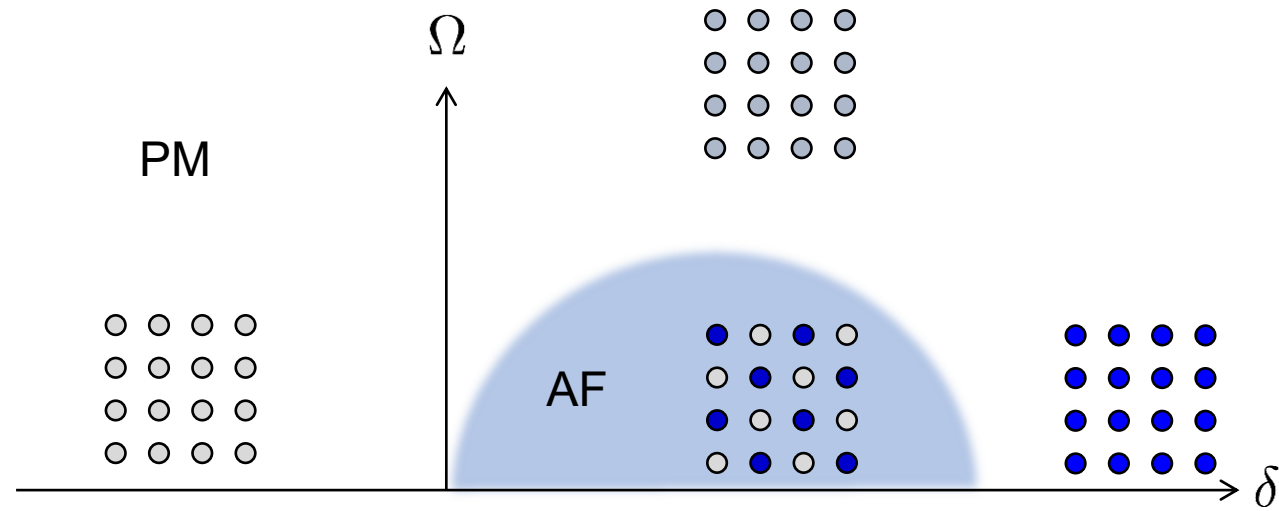


Antiferromagnetic ground state



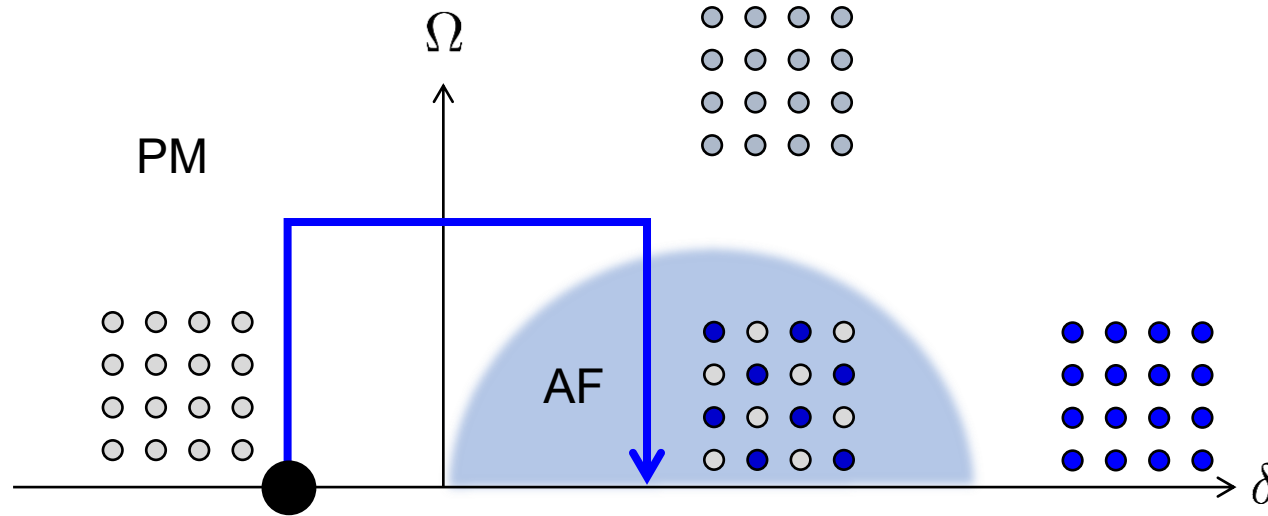
Ising model: adiabatic preparation

Ising AF phase diagram



Ising model: adiabatic preparation

Ising AF phase diagram

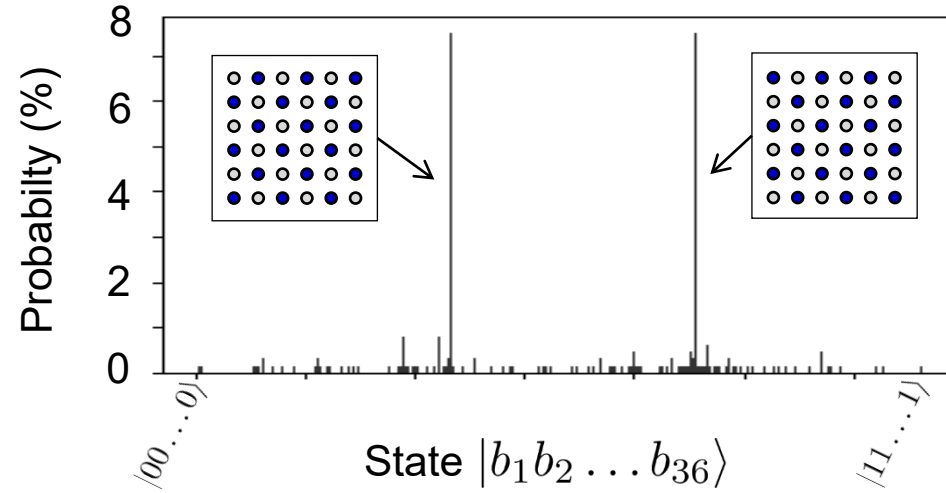
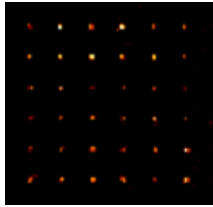


$$H = \sum_i \left(\frac{\hbar\Omega}{2} \sigma_x^i - \hbar\delta n^i \right) + \sum_{i < j} \frac{C_6}{R_{ij}^6} n_i n_j$$

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

'Adiabatic' preparation on a square array

6×6
square array

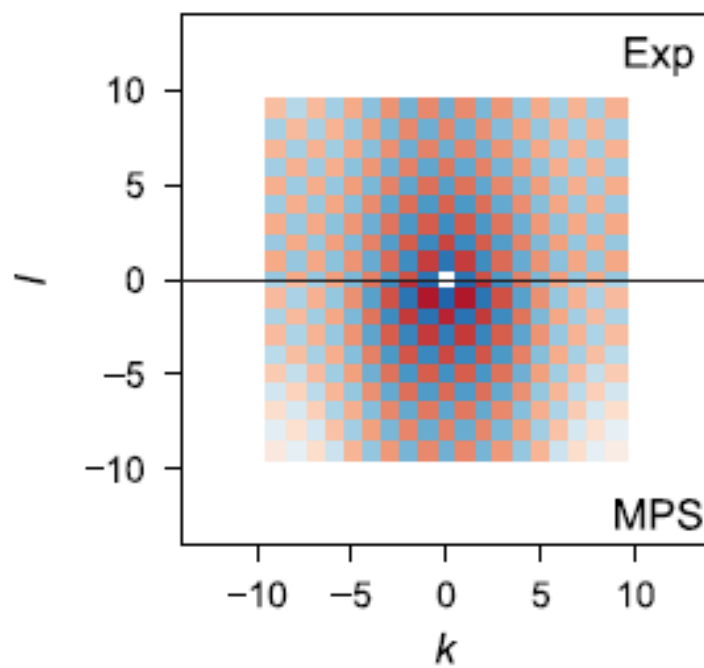


$2^{36} \approx 7 \cdot 10^{10}$ states!

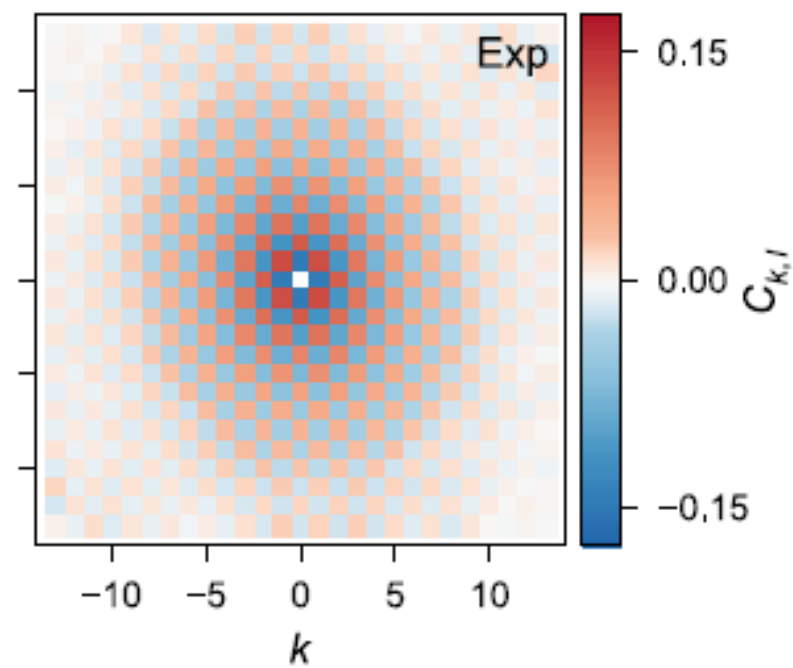
Correlation functions

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

10×10 array



14×14 array



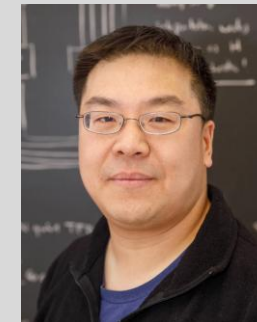
The resonant dipole-dipole interaction: dipolar XY model

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

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

Norm Yao's group (Harvard)

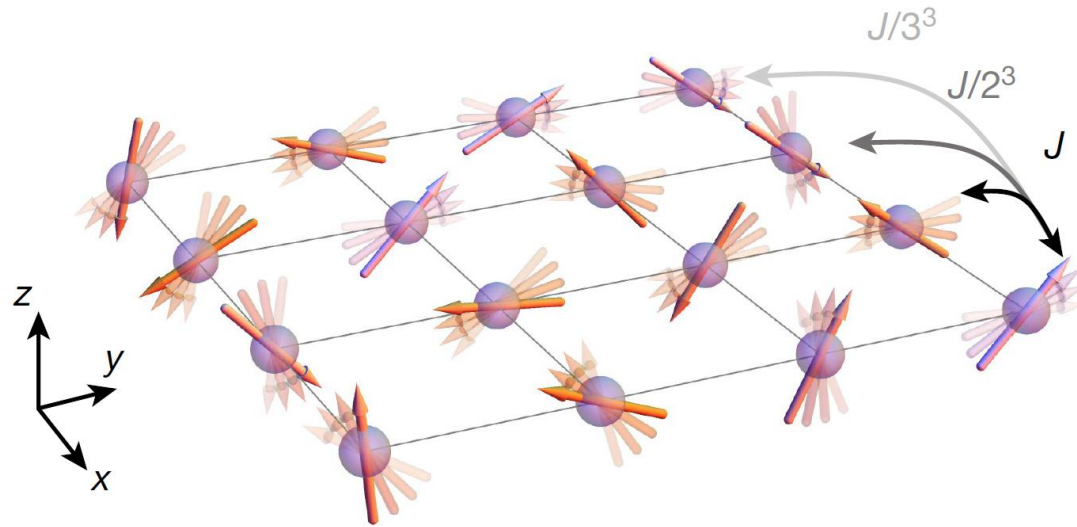
Tommaso Roscilde's group (ENS Lyon)



The resonant dipole-dipole interaction: dipolar XY model



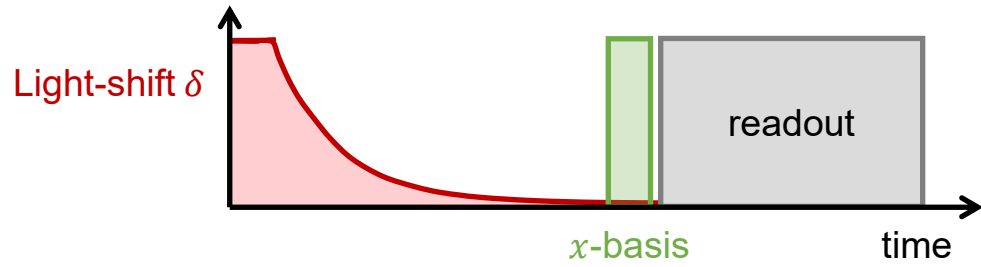
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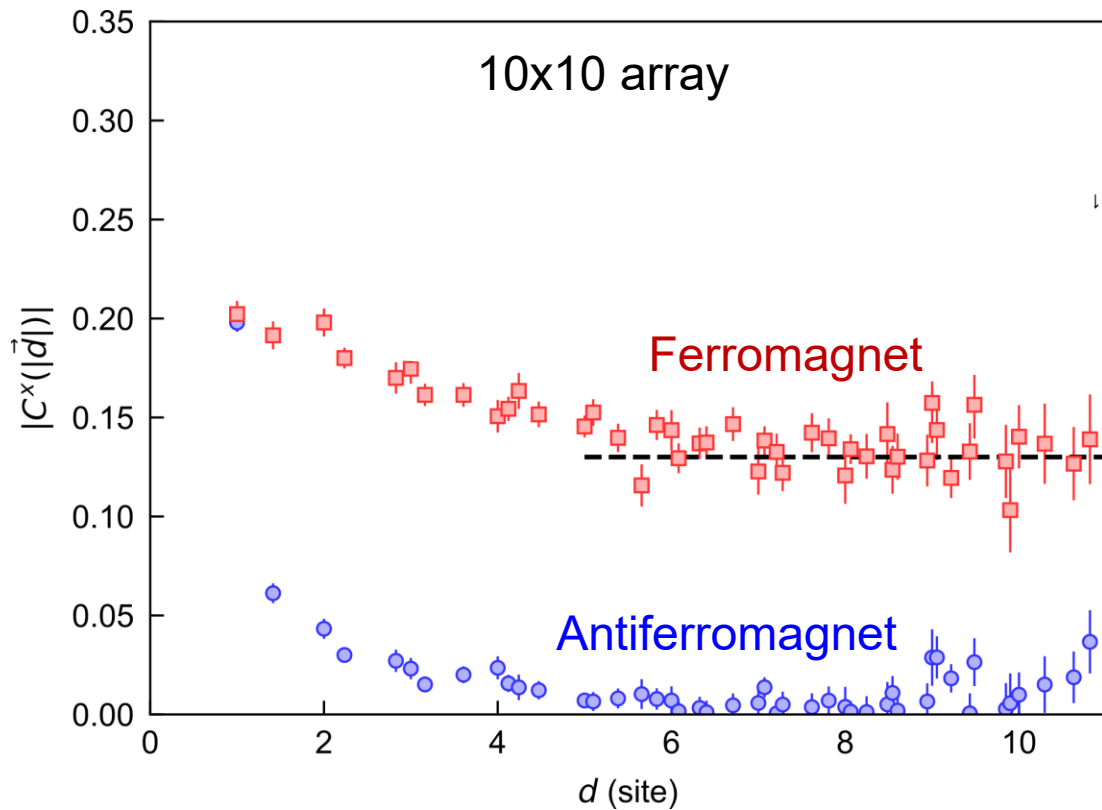
$$H_{\text{XY}} = -J \sum_{i < j} \frac{a^3}{r_{ij}^3} (\sigma_i^x \sigma_j^x + \sigma_i^y \sigma_j^y)$$

- **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

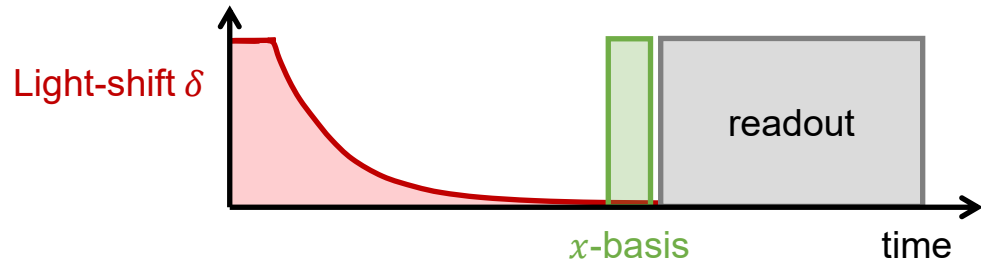


Ferromagnet: Long-range order

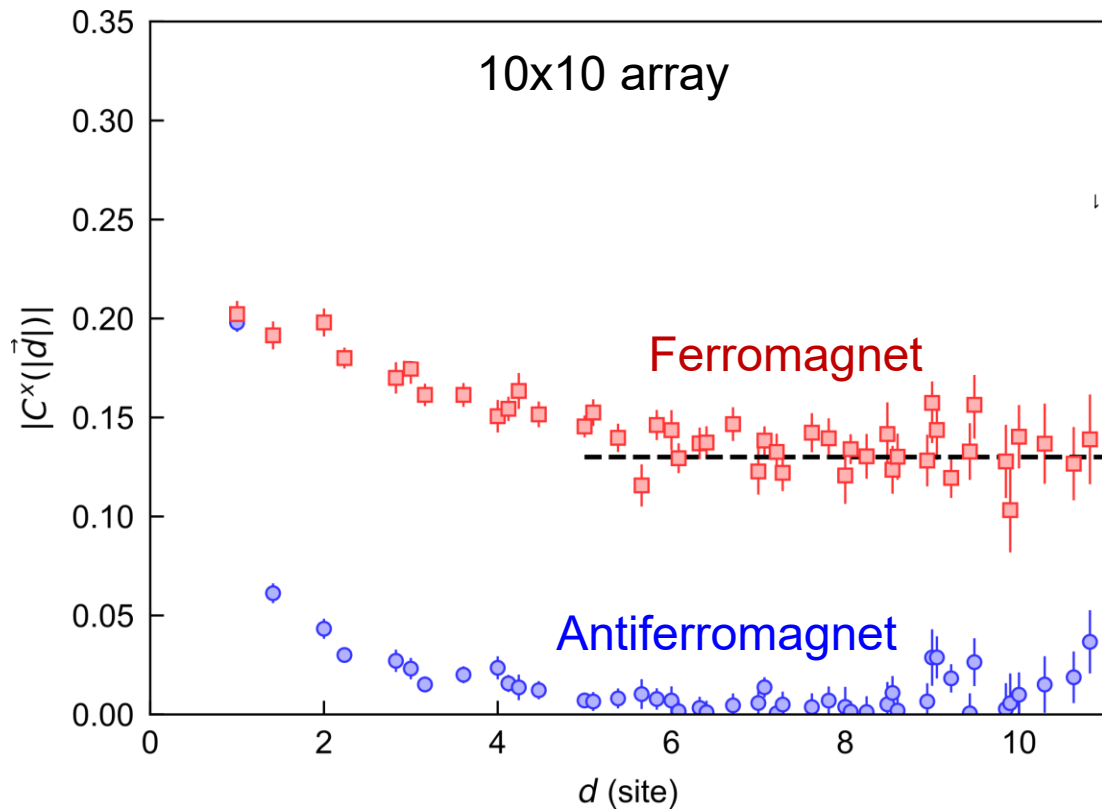
Antiferromagnet: Correlations decay to 0

Crucial role of dipolar couplings!

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



Measure the xx correlations as a function of distance



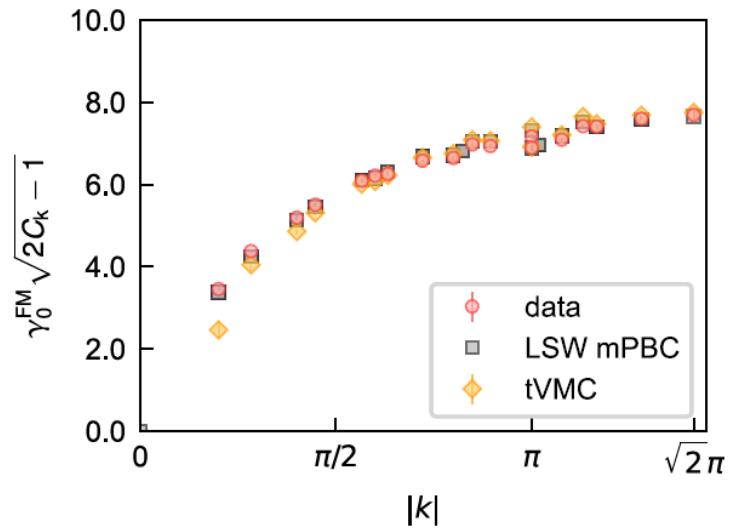
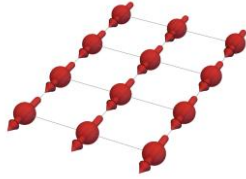
Ferromagnet: Long-range order

Antiferromagnet: Correlations decay to 0

Crucial role of dipolar couplings!

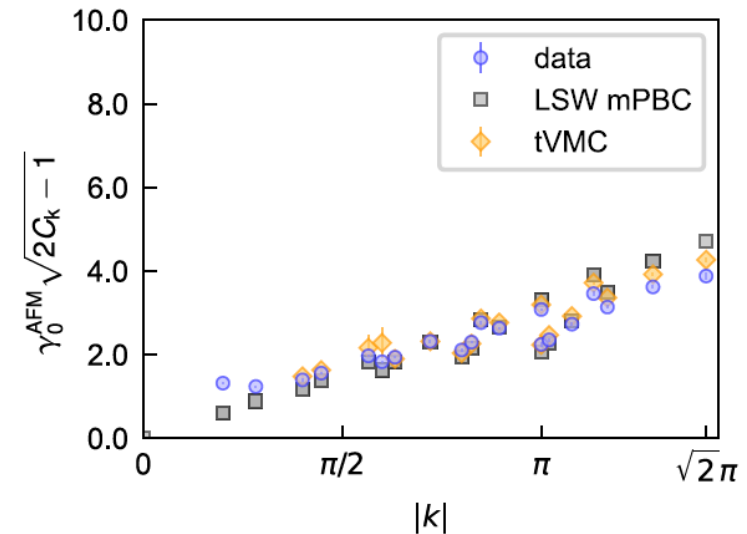
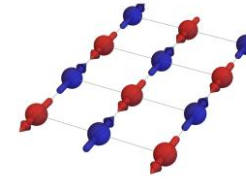
Dispersion relation of spin waves using quench spectroscopy

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 \(2025\)](#)

Doped magnets: bosonic $t - J$ models

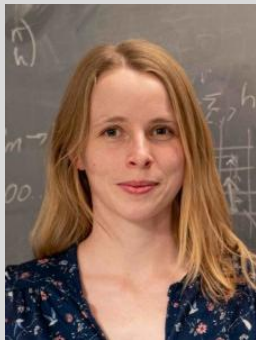
M. Qiao *et al.*, [Nature](#) **644**, 889 (2025)

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

L. Homeier



A. Bohrdt



F. Grusdt



I. Morera



E. Demler



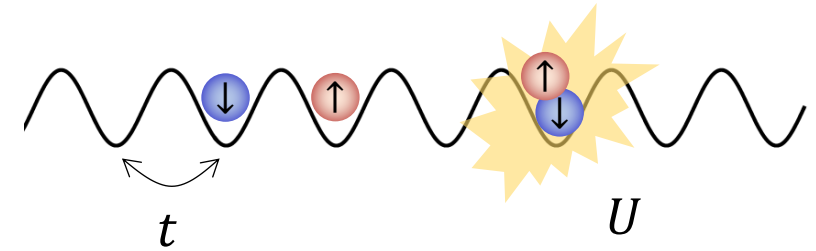
Doped magnets: bosonic $t - J$ models



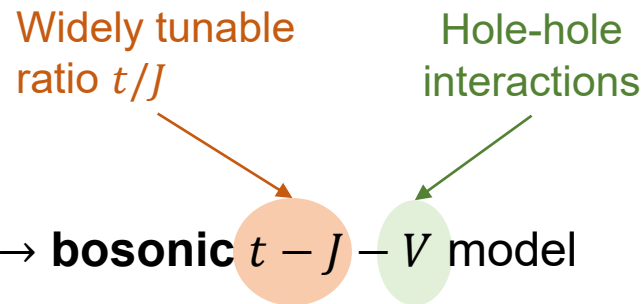
Doped magnets: $t - J$ model

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

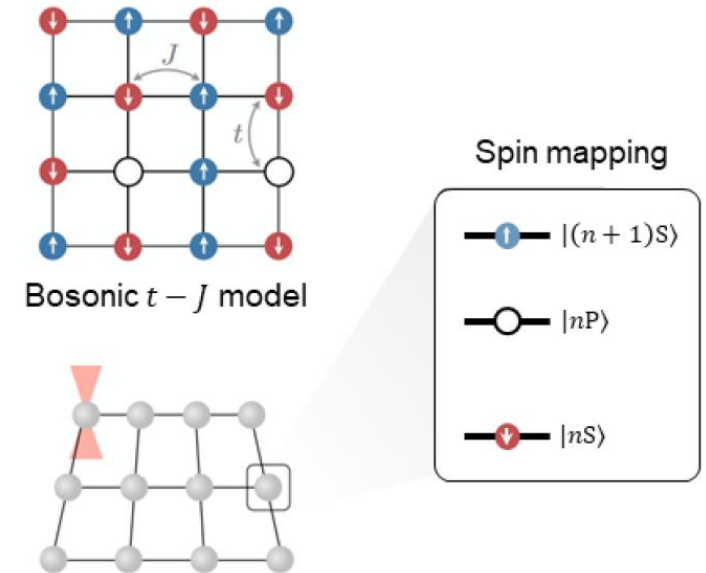


Interplay between hole tunneling t and spin ordering J

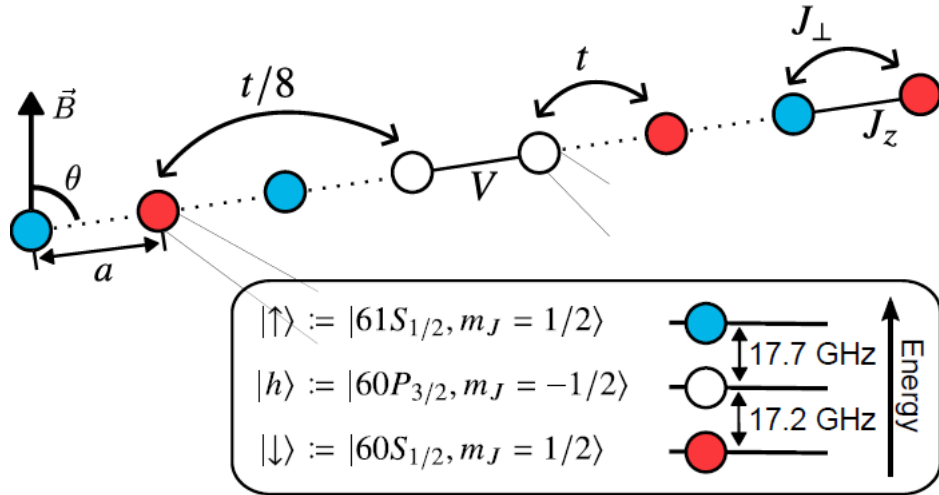


Proposal: three Rydberg levels \rightarrow bosonic $t - J - V$ model

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



Mapping onto three Rydberg states



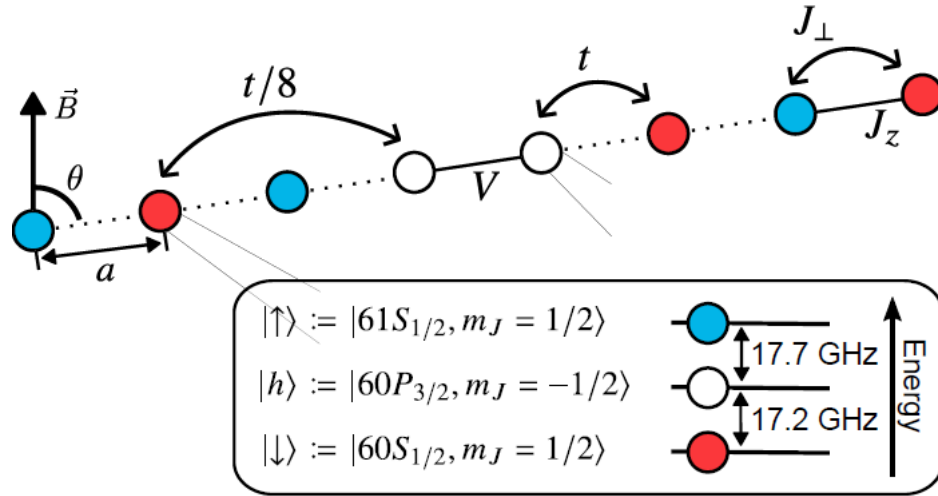
$$\hat{H}_{tJV} = \hat{H}_t + \hat{H}_J + \hat{H}_V,$$

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

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

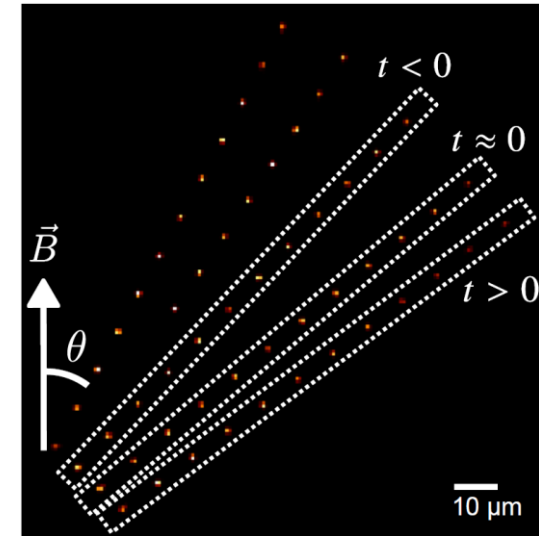
$$\hat{H}_V = \sum_{i < j} \frac{V}{r_{ij}^6} \hat{n}_i^h \hat{n}_j^h. \quad \text{van der Waals interactions } 60P / 60P$$

Mapping onto three Rydberg states



Tunability:

Change θ to tune tunneling term t



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

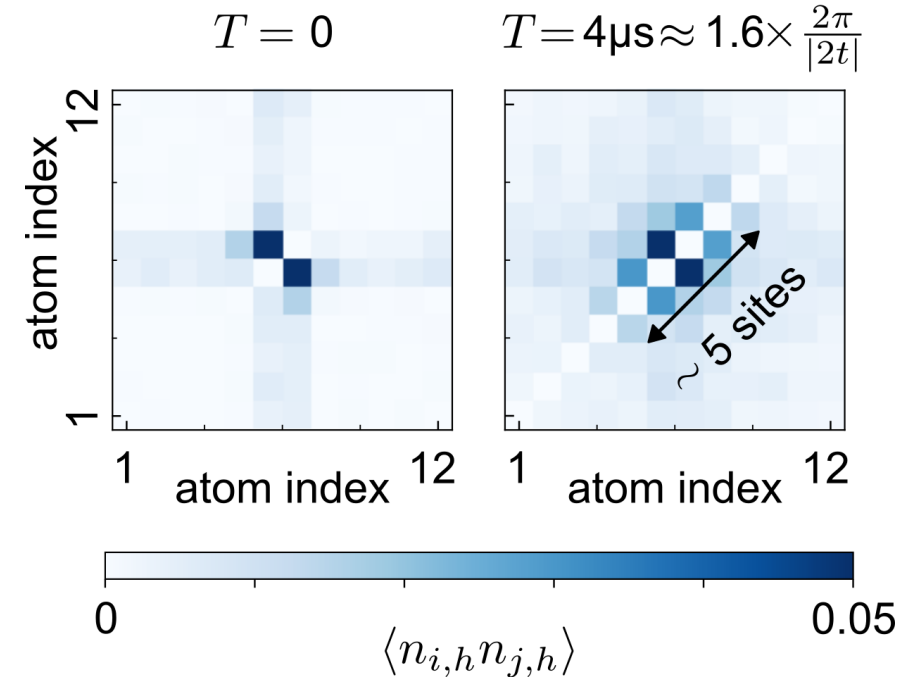
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$$\hat{H}_V = \sum_{i < j} \frac{V}{r_{ij}^6} \hat{n}_i^h \hat{n}_j^h. \quad \text{van der Waals interactions } 60P / 60P$$

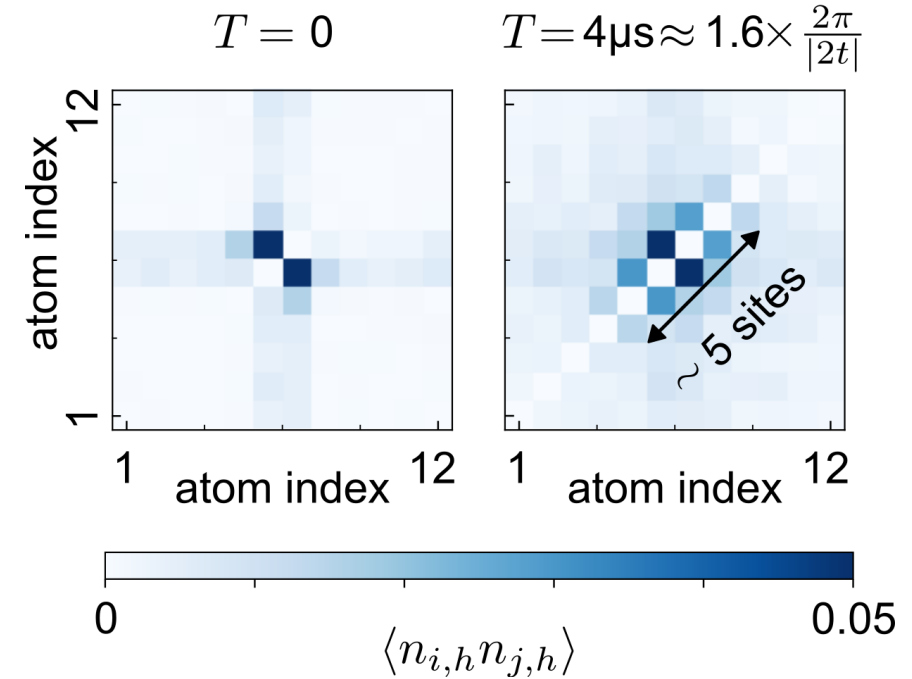
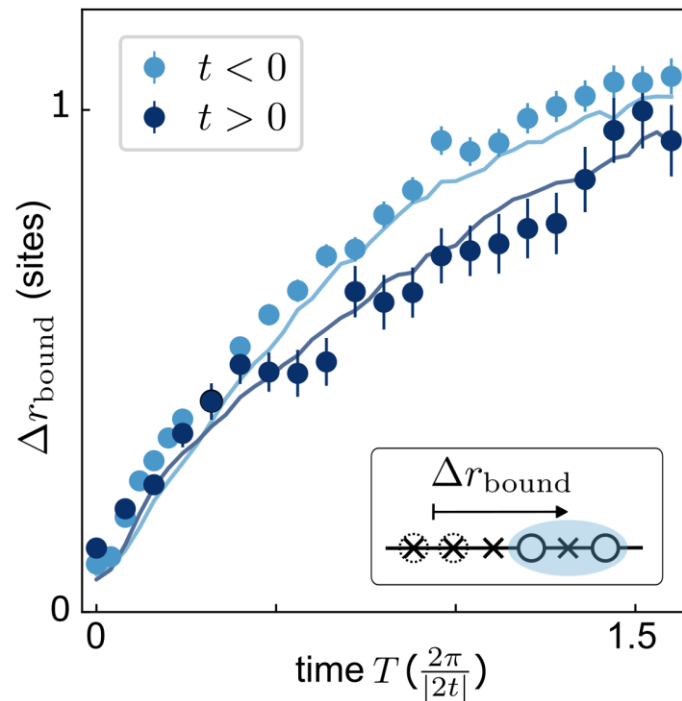
Hole-hole bound states in a 12-site chain

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!