Quantum simulation and computation with cold atoms

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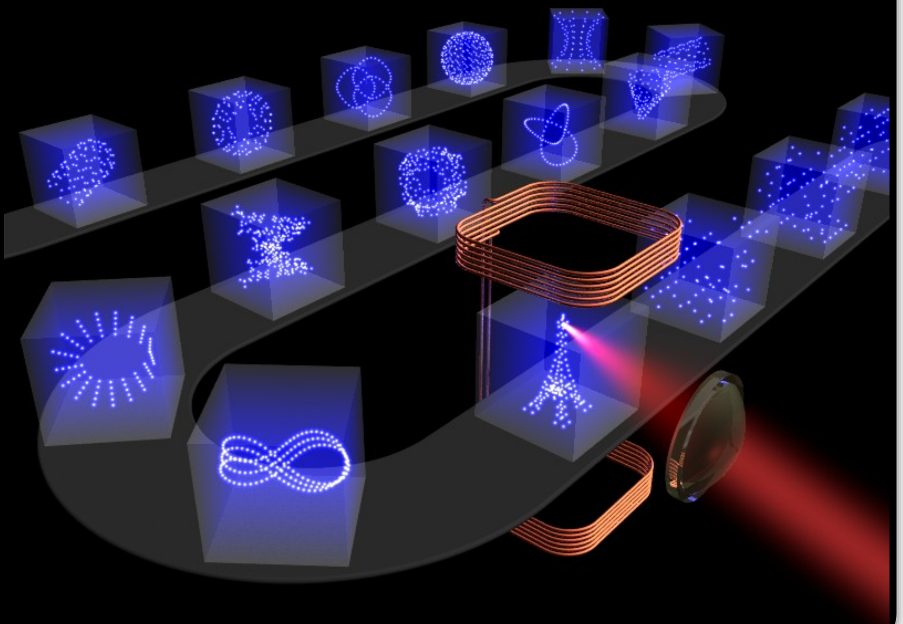


Spring School on Near-Term Quantum Computing

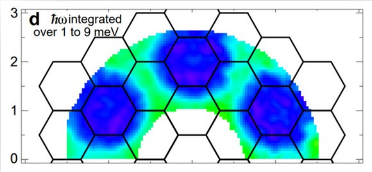
Benasque Science Center, Apr 14 - Apr 27, 2024

Many-body quantum systems: challenges

Goal: Understand ensembles of interacting quantum particles

Magnetism

Nature **492**, 406 (2012)

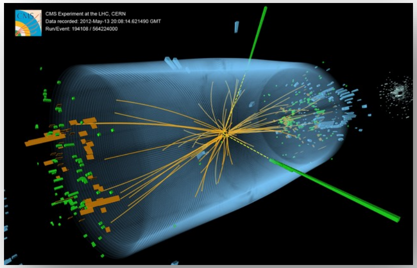


Herbertsmithite

Superconductivity

Charles O'Rear Getty Images

High energy physics



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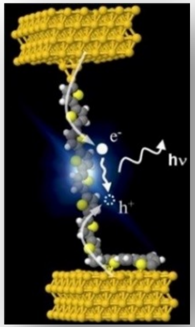
Transport



PRL 112, 047403 (2014)

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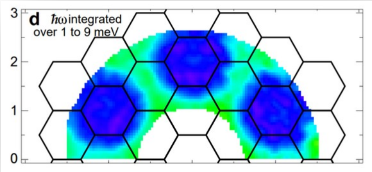

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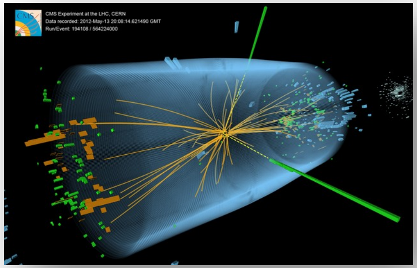

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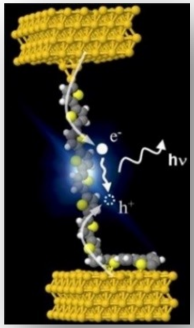

PRL 112, 047403 (2014)

Open questions: Phase diagram, dynamics (hard for N>40…) Topology, disorder, entanglement,…

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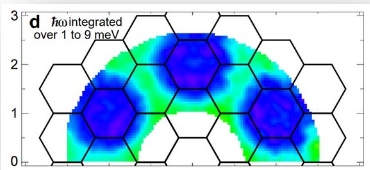

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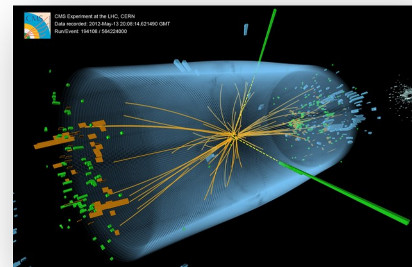

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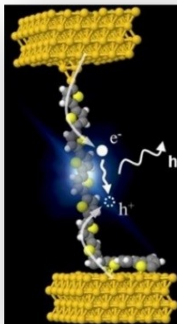

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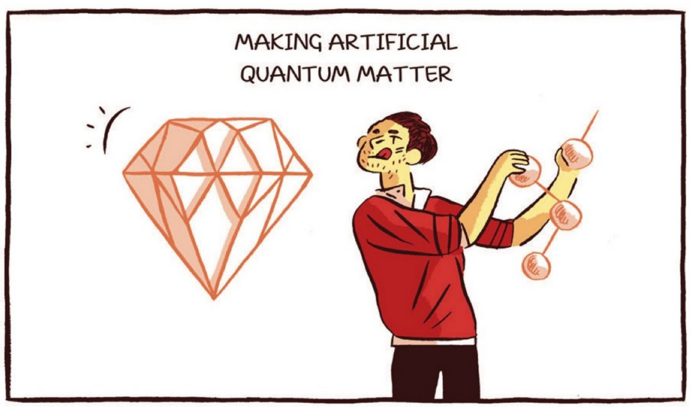

Héloïse Chochois, Labex PALM

R.P. Feynman

Use experimental control to

Implement **many-body Hamiltonians** (including “mathematical” ones...)

Larger **tunability** than « real » systems

= QUANTUM SIMULATION

Analog vs digital quantum simulation

Analog

The platform implement directly H_{model}

$$|\psi(t)\rangle = \exp\left(-\frac{i}{\hbar}\int_0^t H_{\text{mod}}(t')dt'\right)|\psi(0)\rangle$$

e.g. Fermi Hubbard, spin models, electrons in B-fields…

Georgescu, Rev. Mod. Phys. (2014)

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Digital

H_{model} is synthesized digitally

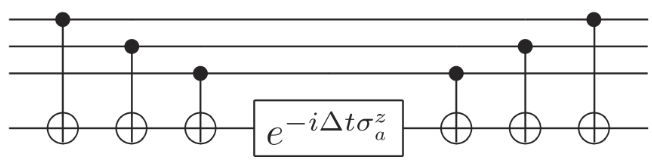
$$H_{\text{model}} = \sum_{i=1}^{l} H_i$$

e.g. single / 2 qbit operations

$$e^{-iH_{\text{mod}}t} \approx \left(e^{-iH_1 t/n} e^{-iH_2 t/n} \ldots e^{-iH_3 t/n}\right)^n$$

= "universal" quantum simulation

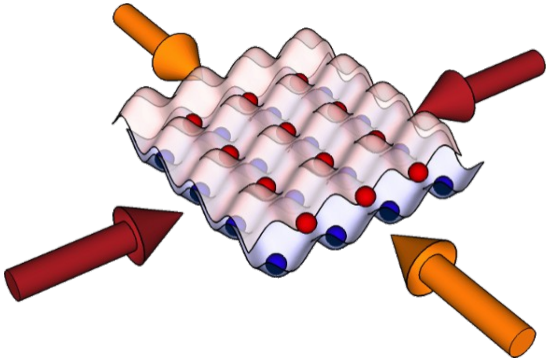
Ex:



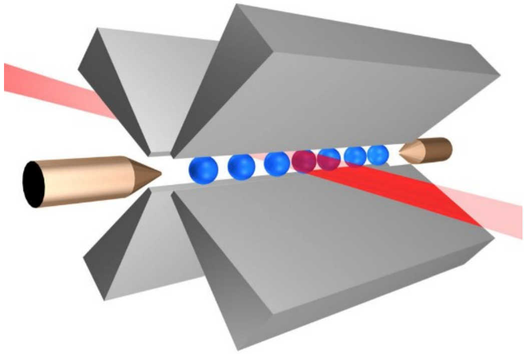
$$H_{\text{mod}} = \sigma_1^z \otimes \sigma_2^z \otimes \sigma_3^z$$

Georgescu, Rev. Mod. Phys. (2014)

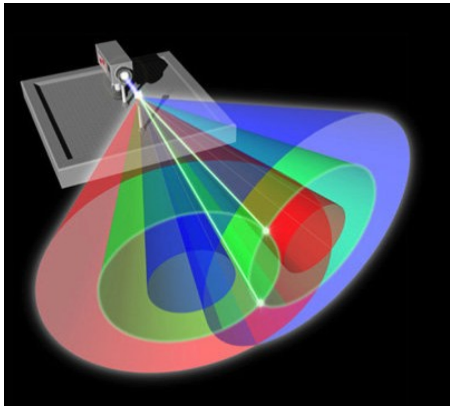
Quantum state engineering with individual systems



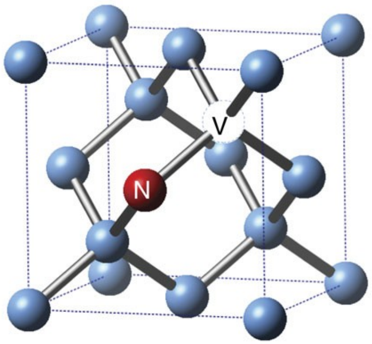
Cold atoms and molecules



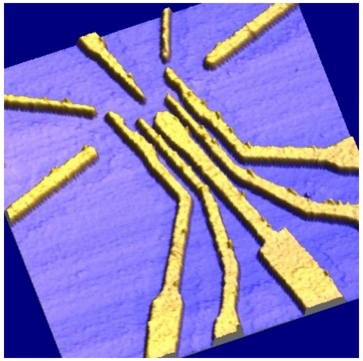
Trapped ions



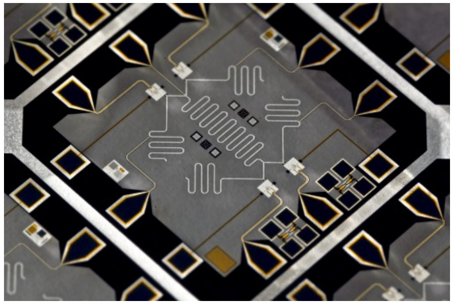
Photons



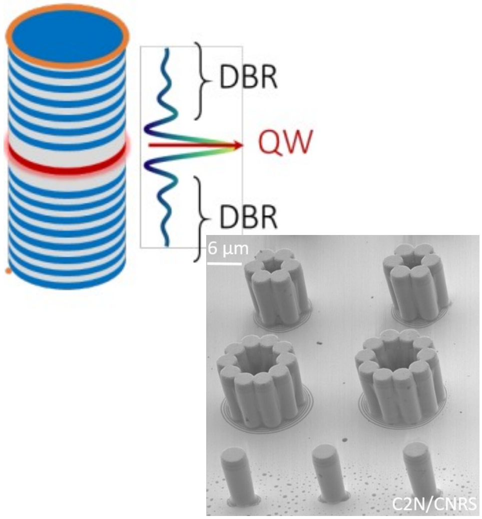
NV centers



Quantum dots



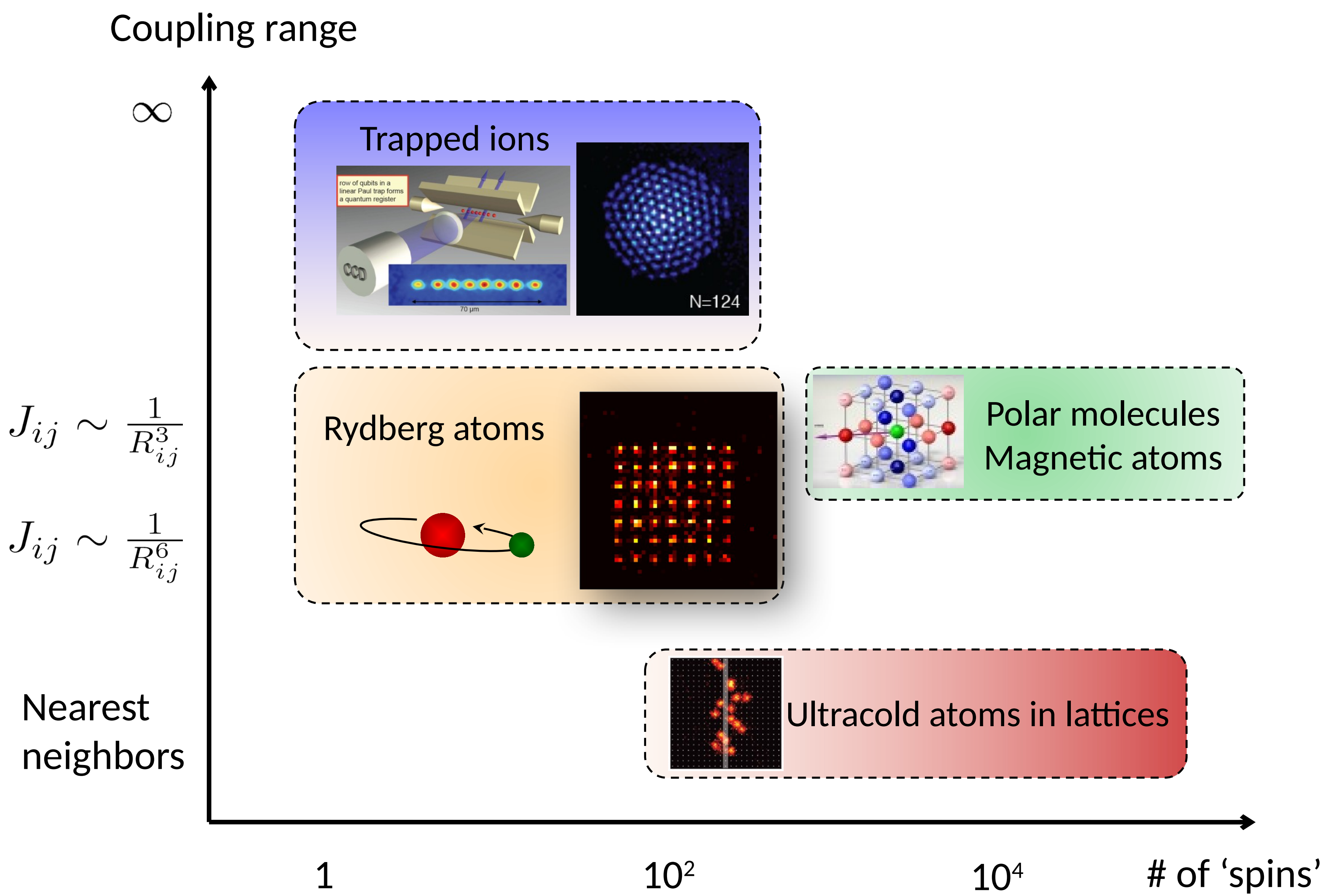
Superconducting qubits



Polaritons condensates

See e.g. Hazzard *et al.*, PRA **90**, 063622 (2014)

Atom arrays



See e.g. Hazzard *et al.*, PRA **90**, 063622 (2014)

Atom arrays

Coupling range

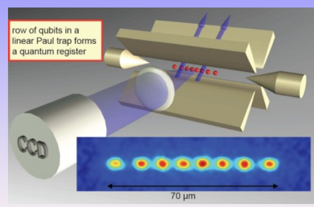
∞

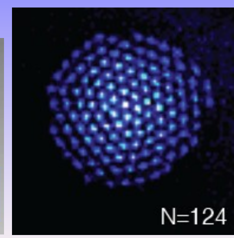
$J_{ij} \sim \frac{1}{R_{ij}^3}$

$J_{ij} \sim \frac{1}{R_{ij}^6}$

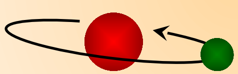
Nearest neighbors

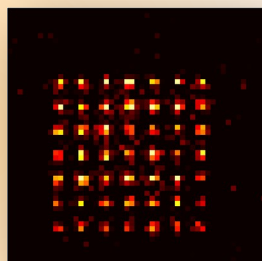
Trapped ions

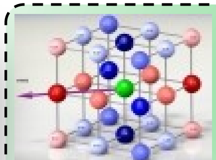




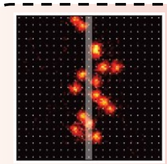
Rydberg atoms







Polar molecules
Magnetic atoms



Ultracold atoms in lattices

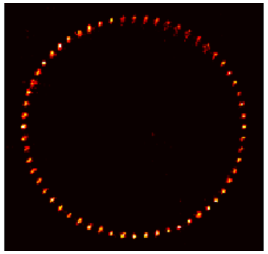
1 | 10^2 | 10^4 | # of 'spins'

- **Scalable:** beyond 1000 particles
- **Addressable:** local manipulation and measurement
- **Programmable:** controlled geometry, interactions…

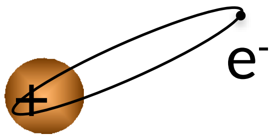
See e.g. Hazzard *et al.*, PRA **90**, 063622 (2014)

Outline

1. **Arrays of individual atoms**



2. **Rydberg atoms and their interactions**



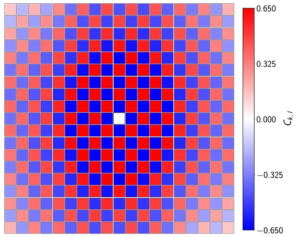
3. **Examples of quantum simulations**

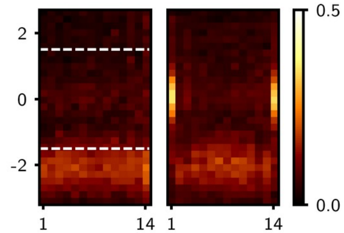
   A. Exploration of phase diagrams

   B. Out-of-Equilibrium dynamics

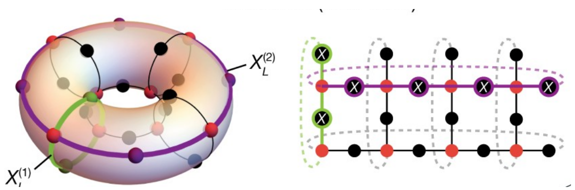
   C. Ground state preparation & squeezing

   D. Synthetic Topological matter





4. **Digital quantum computing**



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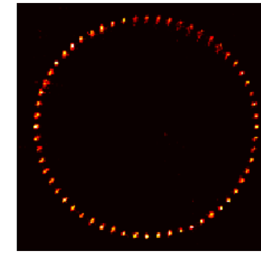

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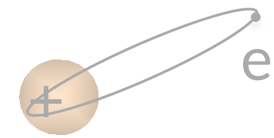

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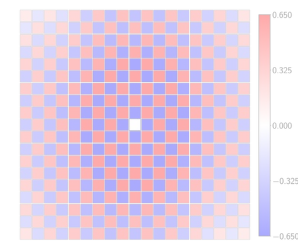

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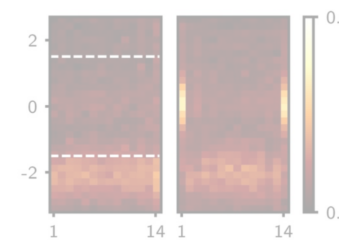

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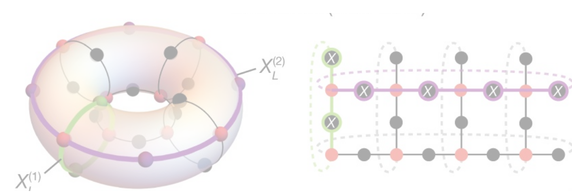
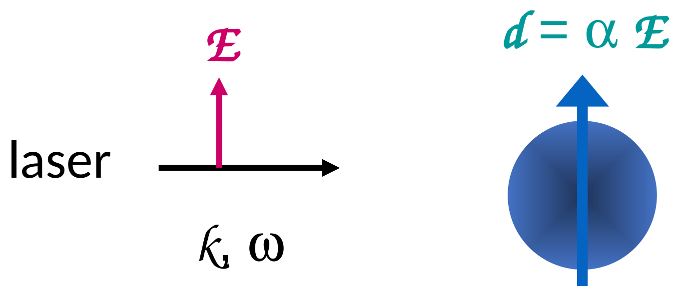


Optical dipole trap

Classical



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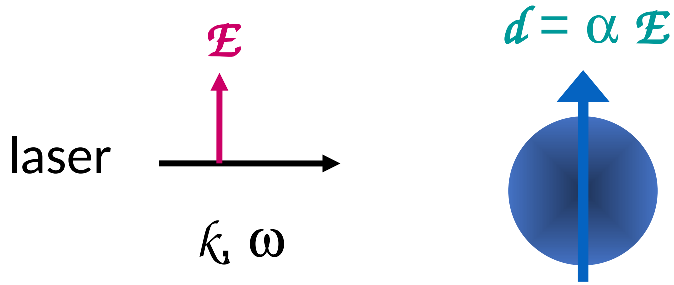
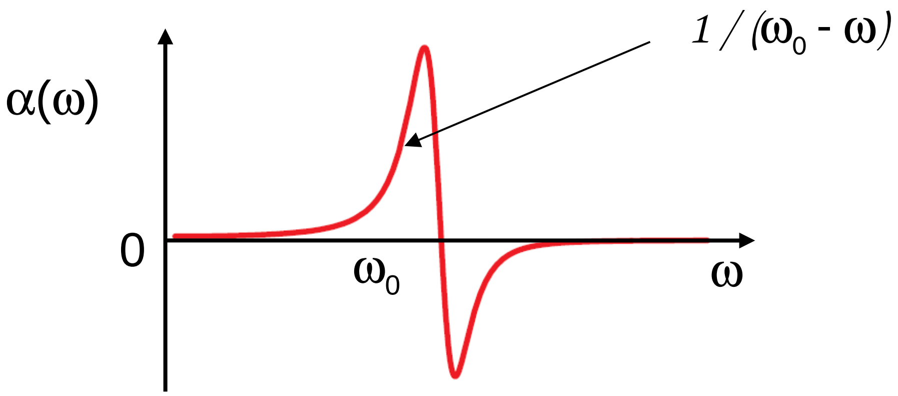


Harmonic oscillator model



Interaction atom - light

$\mathcal{U}(x) \sim - \alpha\, \mathcal{E}(x)^2$

⇒ Conservative POTENTIAL

Optical dipole trap

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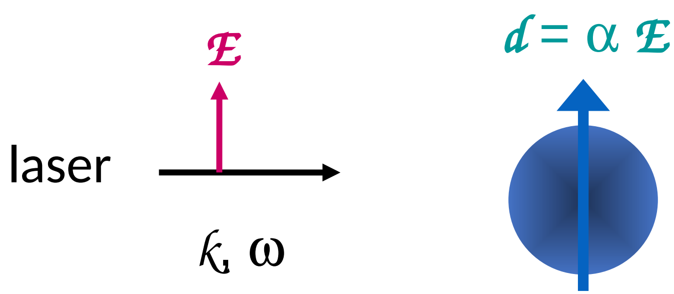

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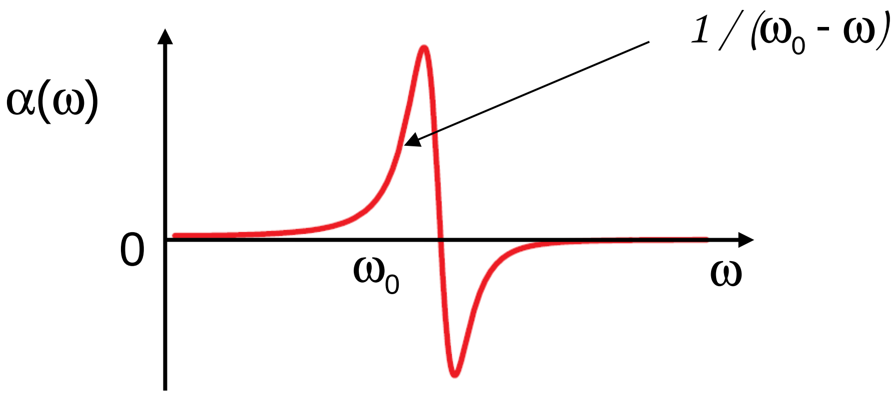

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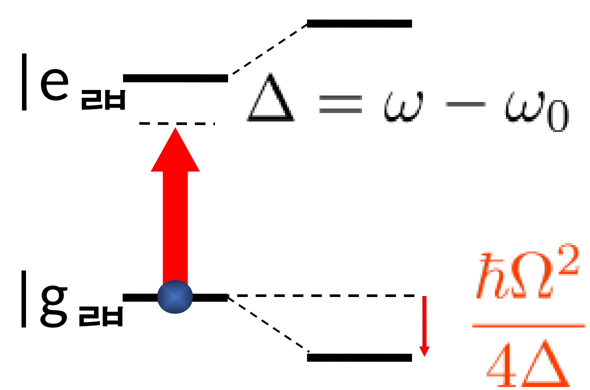
Quantum

$$\hbar\Omega = d.E$$

$$d = \langle e|\hat{D}|g\rangle$$

$\omega_0 > \omega$



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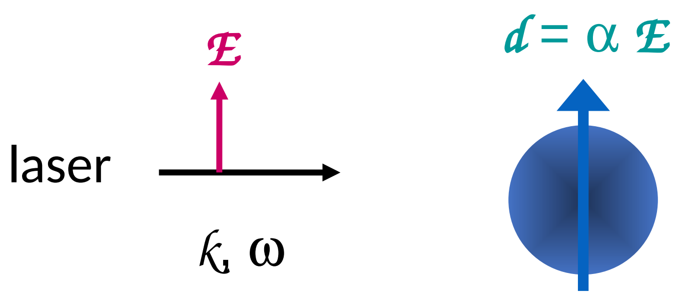

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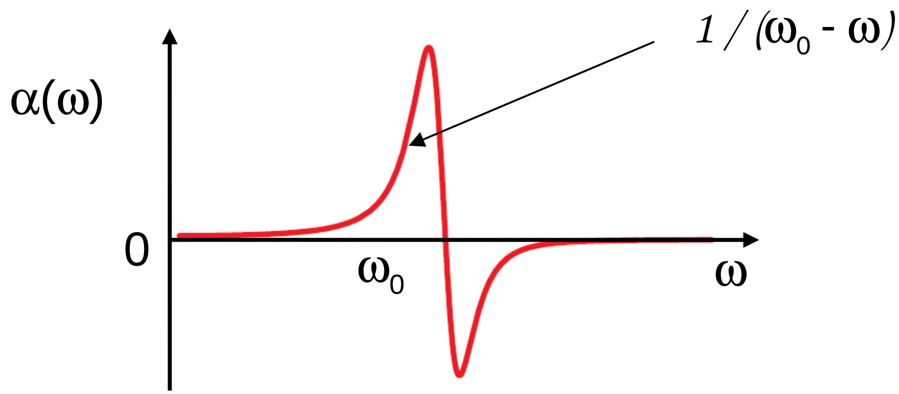

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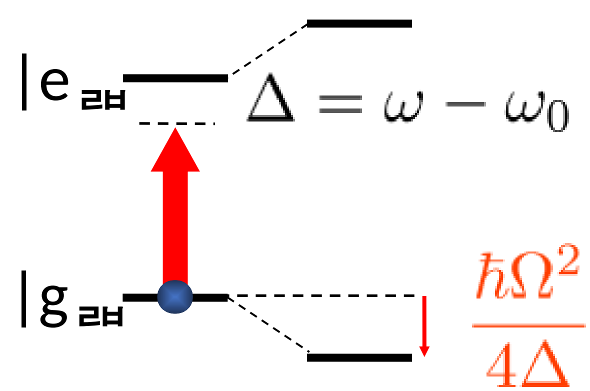
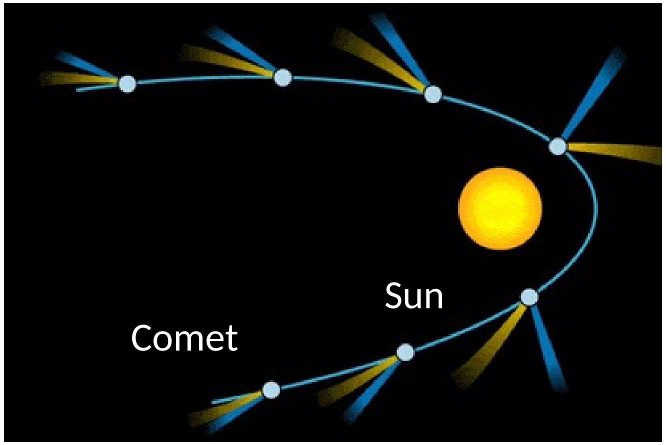


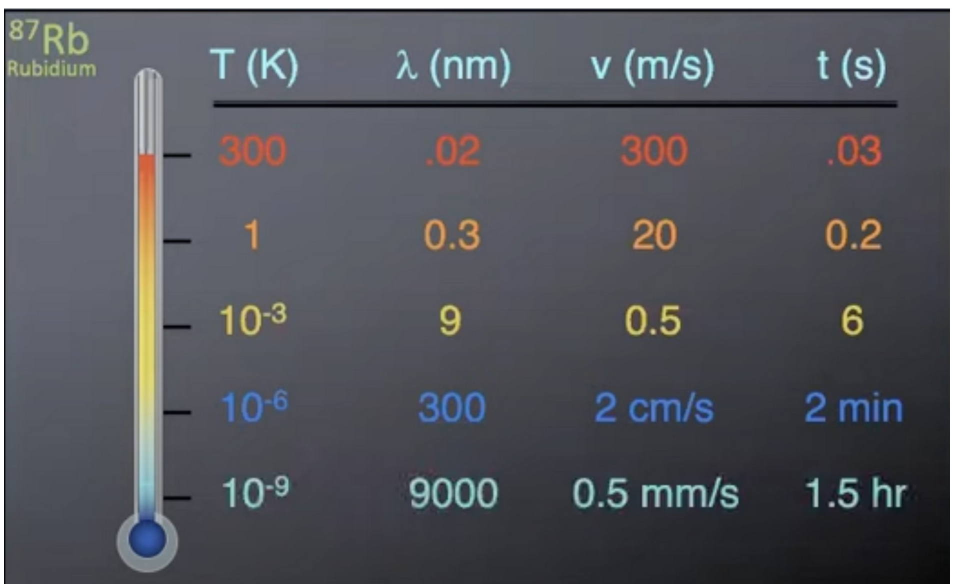
Trap depth ~ 100 µK – 1 mK

⇒ cold atoms

Laser cooling of neutral atoms

Radiation pressure





T (K)	λ (nm)	v (m/s)	t (s)
300	.02	300	.03
1	0.3	20	0.2
10^{-3}	9	0.5	6
10^{-6}	300	2 cm/s	2 min
10^{-9}	9000	0.5 mm/s	1.5 hr

The Nobel Prize in Physics 1997

Photo from the Nobel Foundation archive.
Steven Chu
Prize share: 1/3

Photo from the Nobel Foundation archive.
Claude Cohen-Tannoudji
Prize share: 1/3

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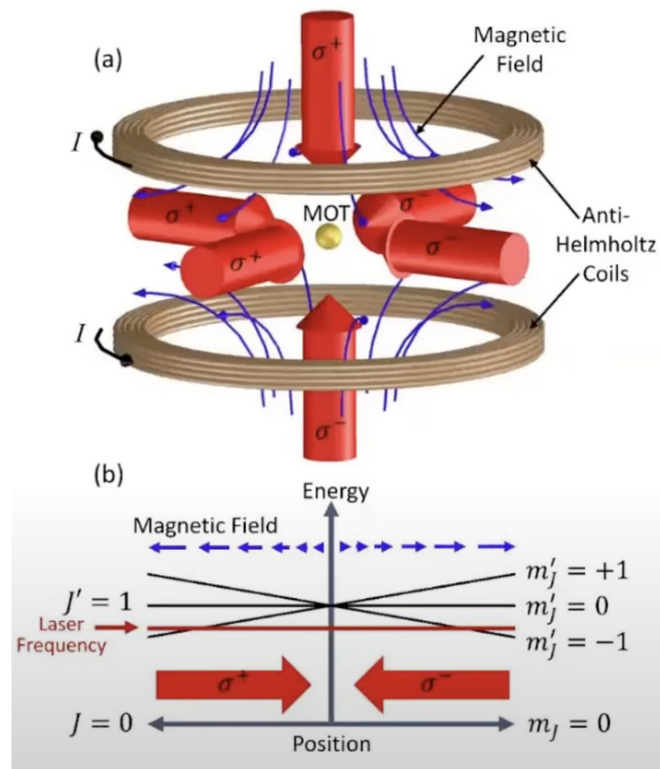
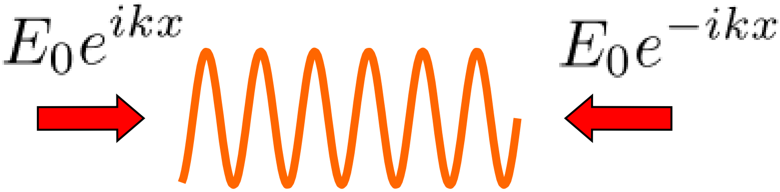
William D. Phillips
Prize share: 1/3



Ultra-cold atoms in optical lattices

Dipole force: $\mathbf{F} \propto -\nabla I(\mathbf{r})$



$$I(x) = 2E_0^2(1 + \cos 2kx)$$

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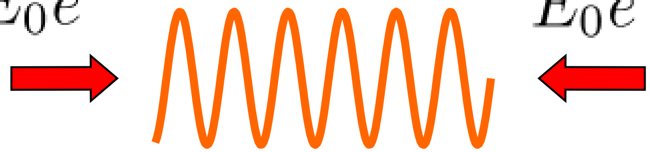
$E_0 e^{ikx}$ $E_0 e^{-ikx}$



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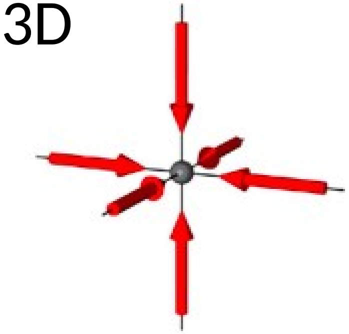
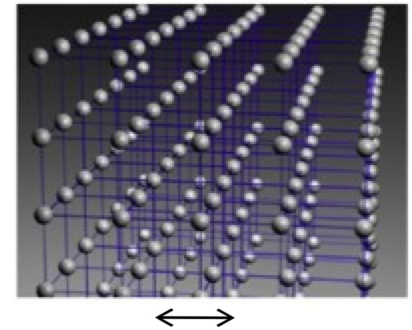
3D





$\lambda/2 = 0.5\ \mu\text{m}$

(M. Greiner thesis)

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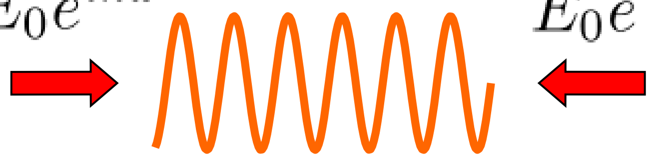
$E_0 e^{ikx}$ $E_0 e^{-ikx}$



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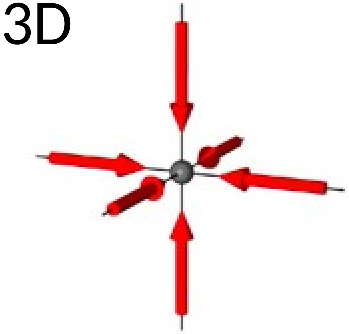
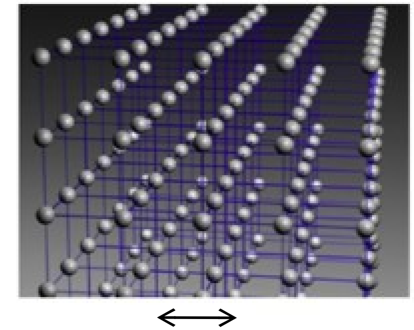
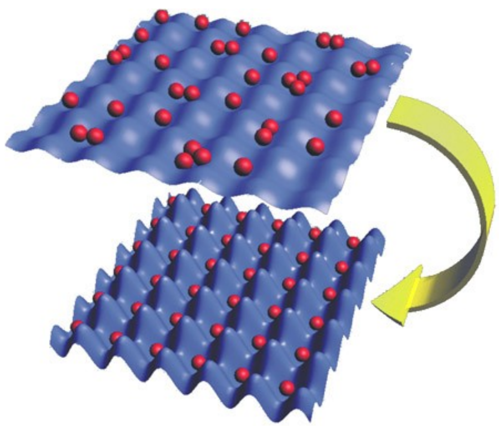




λ/2 = 0.5 μm

(M. Greiner thesis)

Each site contains 1 atom!



Boson (Rb, Na, ^{7}Li, ^{39}K, ^{4}He*),
Fermion (^{6}Li, ^{40}K),
Magnetic atoms (Cr, Dy…)

Ultra-cold atoms in optical lattices

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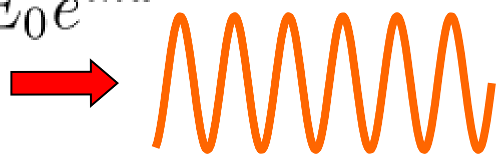
$E_0 e^{ikx}$ $E_0 e^{-ikx}$



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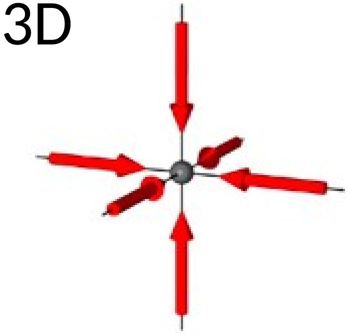
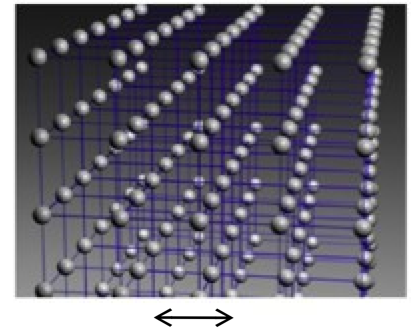
3D

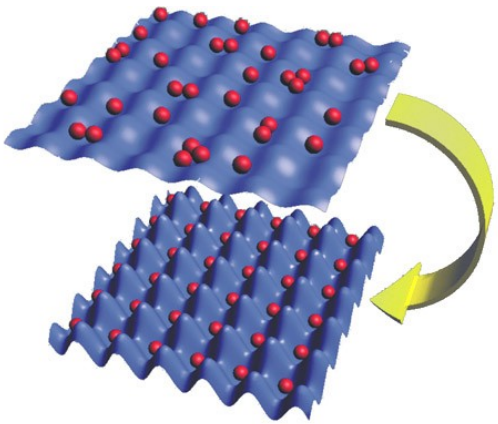




λ/2 = 0.5 μm

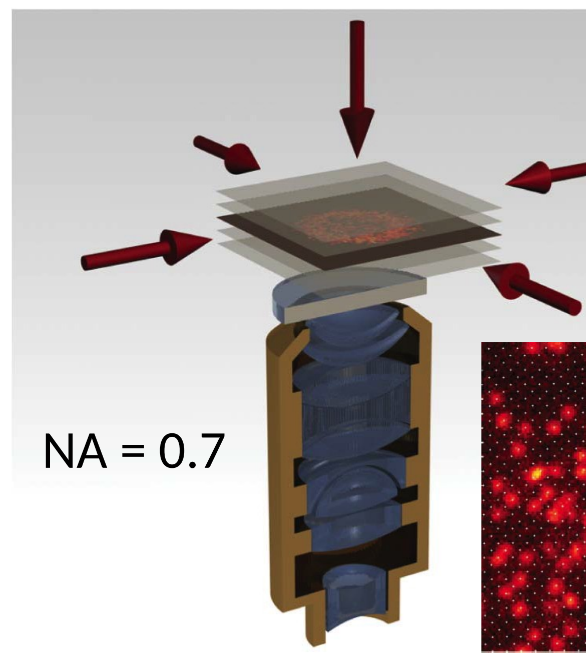
(M. Greiner thesis)

Each site contains 1 atom!



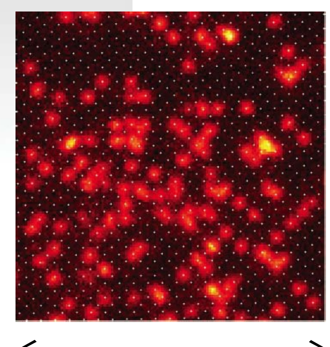
Boson (Rb, Na, ^{7}Li, ^{39}K, ^{4}He*),
Fermion (^{6}Li, ^{40}K),
Magnetic atoms (Cr, Dy…)

Quantum gas microscope



Single-site resolution (< 1 μm)

NA = 0.7



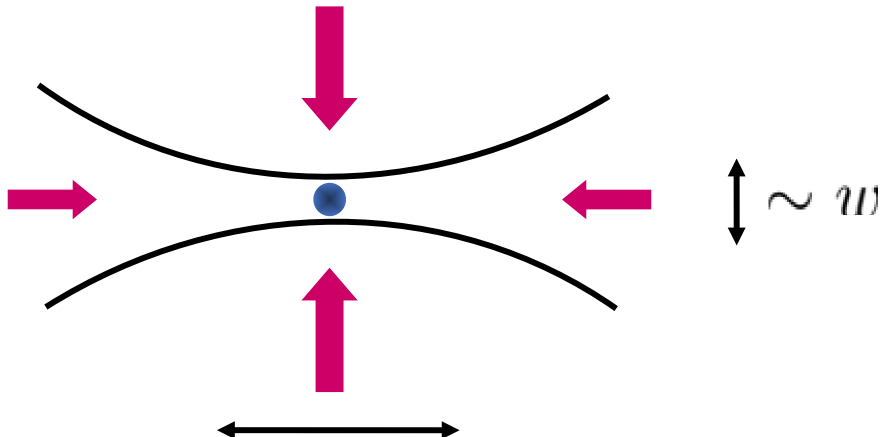
16 μm

Harvard, MPQ

Optical tweezers: trapping in 3D

High field seekers $\omega < \omega_0$

Gaussian beam

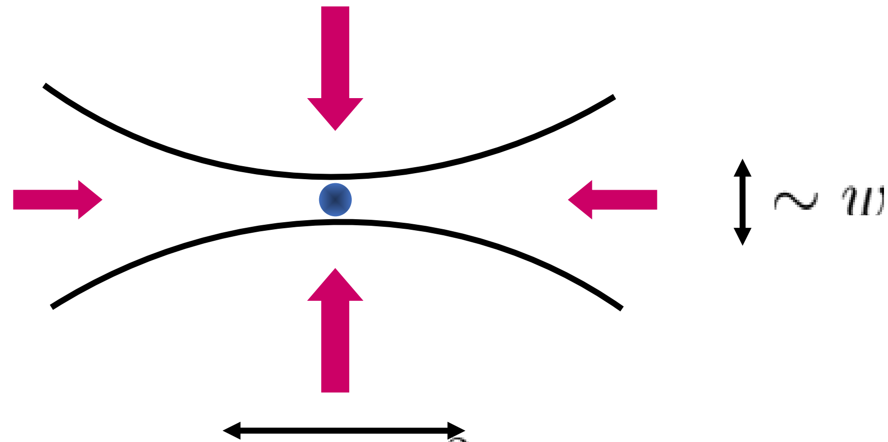


$$z_R = \frac{\pi w^2}{\lambda}$$

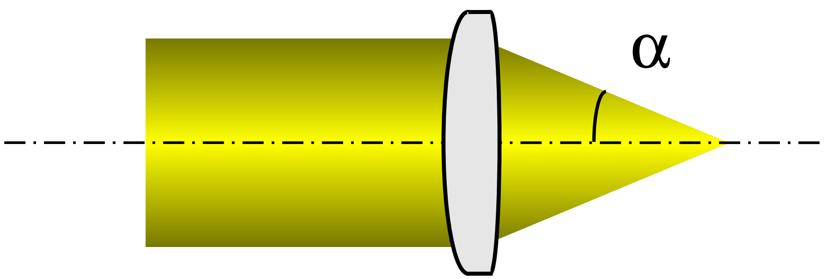
Optical tweezers: trapping in 3D

High field seekers $\omega < \omega_0$

Gaussian beam



$$z_R = \frac{\pi w^2}{\lambda}$$



NA = sin α
w ~ **λ/NA**

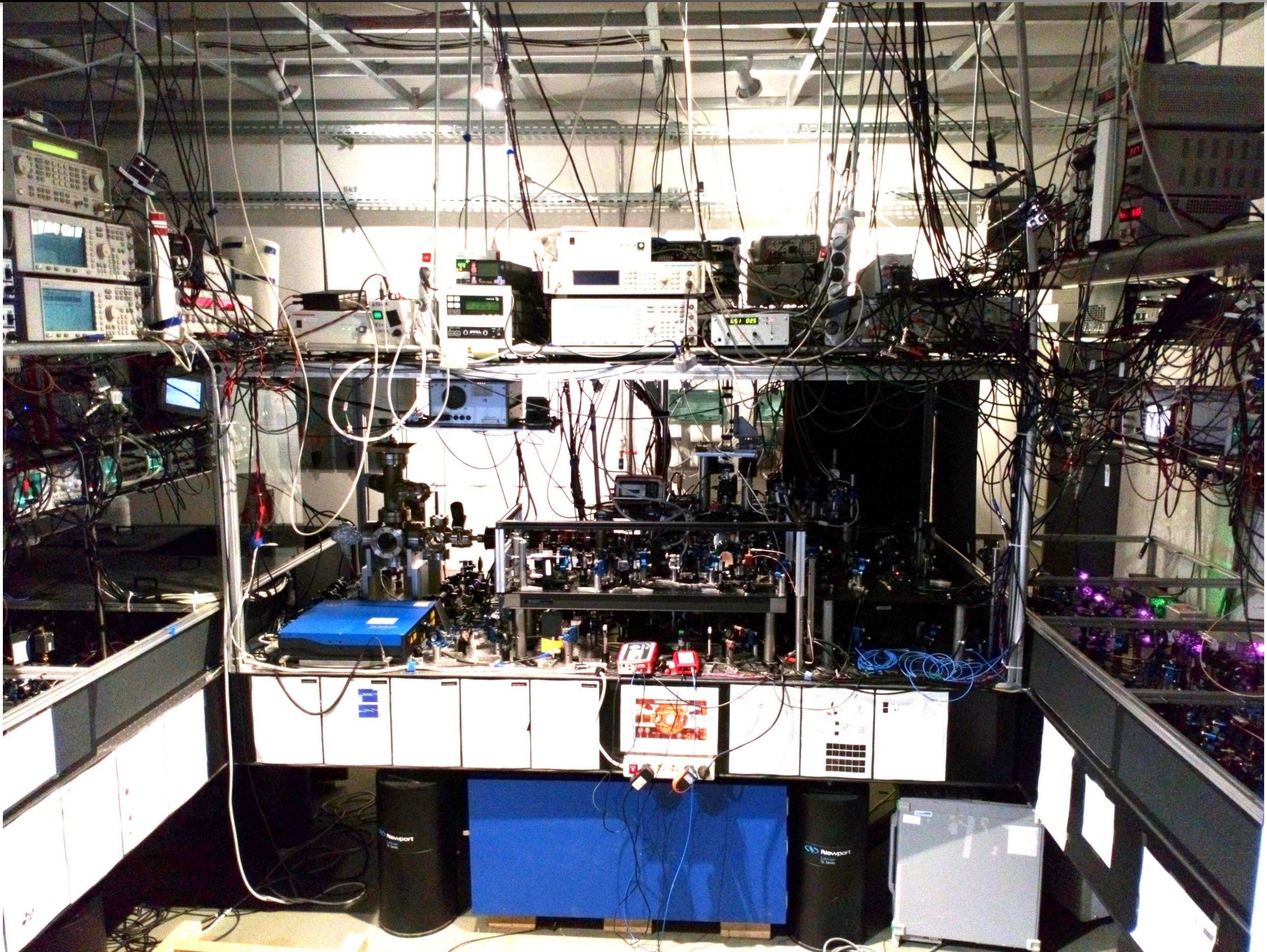
Diffraction limited optics $w \sim \lambda$

Trapping volume $\sim \pi\lambda^3$

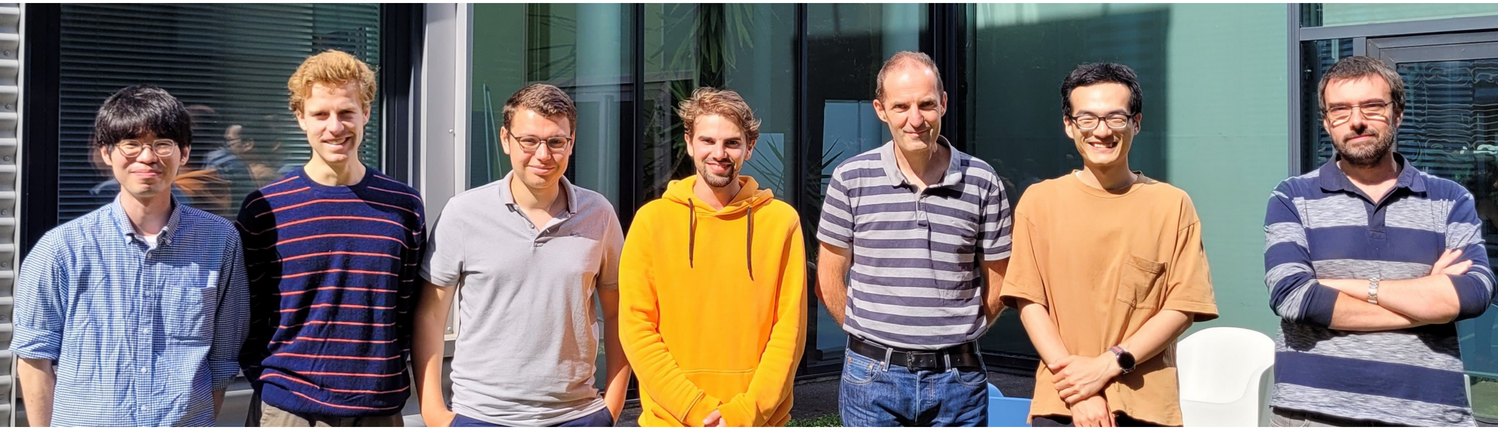
Ex: 1 mW on 1 μm

Trap depth = 1 mK

Experimental setup



The Rydberg team in Palaiseau

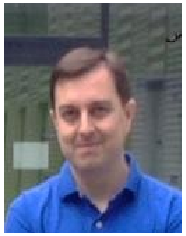


Yeelai Chew — *Gabriel Emperauger* — *Guillaume Bornet* — *Bastien Gély* — *Antoine Browaeys* — *Cheng Chen* — *Thierry Lahaye*

Jamie Boyd

Lucas Leclerc

Mu Qiao



Daniel Barredo

Collaborators (theory):
N. Yao (Harvard),
T. Roscilde (ENS Lyon)
A. Läuchli (Lausanne)
H. P. Büchler (Stuttgart)

Looking for PhDs & postdocs !!

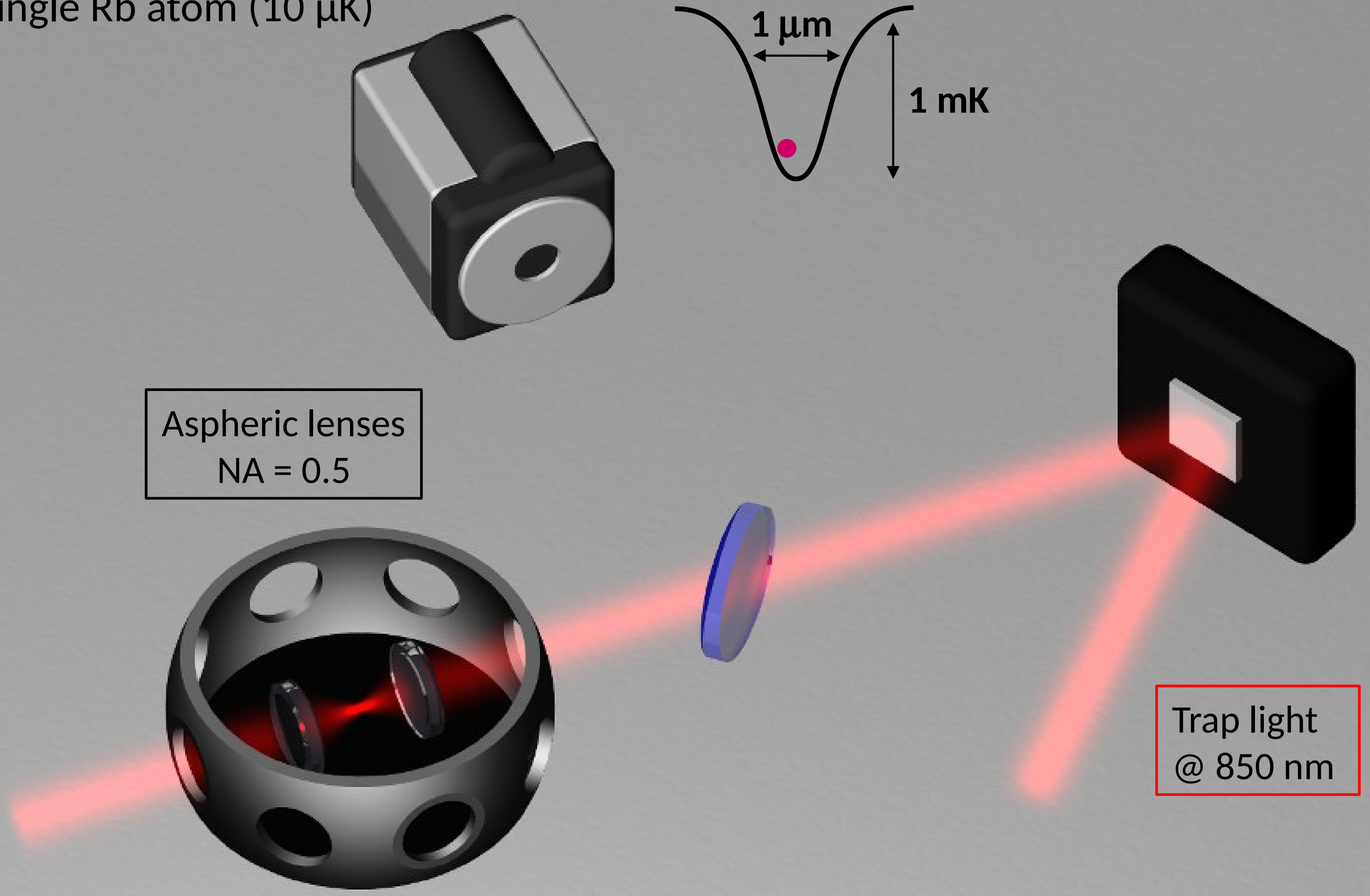
https://atom-tweezers-io.org/

daniel.barredo@csic.es

Funding: PROGRAMME ET EQUIPEMENTS PRIORITAIRES DE RECHERCHE QUANTIQUE — anr — erc — QUANTUM FLAGSHIP — PASQuanS2 — Plan de Recuperación, Transformación y Resiliencia — Agencia Estatal de Investigación — Quantum SPAIN

Individual atoms in optical tweezers

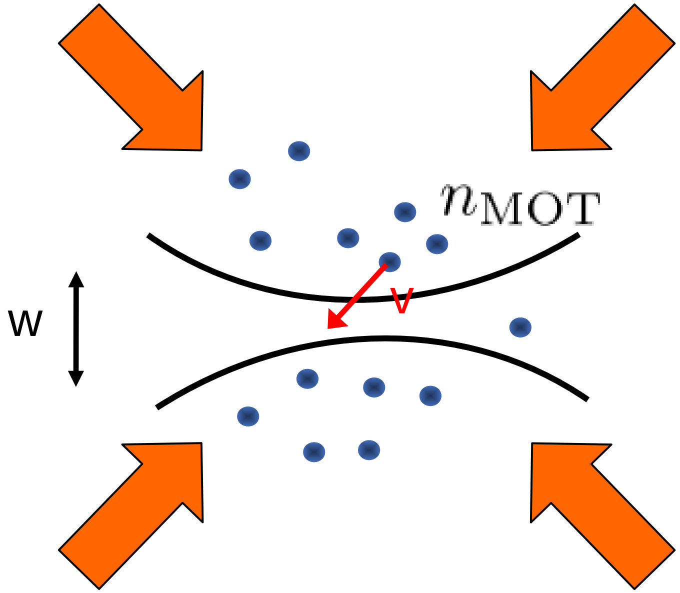
A single Rb atom (10 μK)



Schlosser *et al.*, *Nature* **411**, 1024 (2001)

Loading a tweezer from a MOT

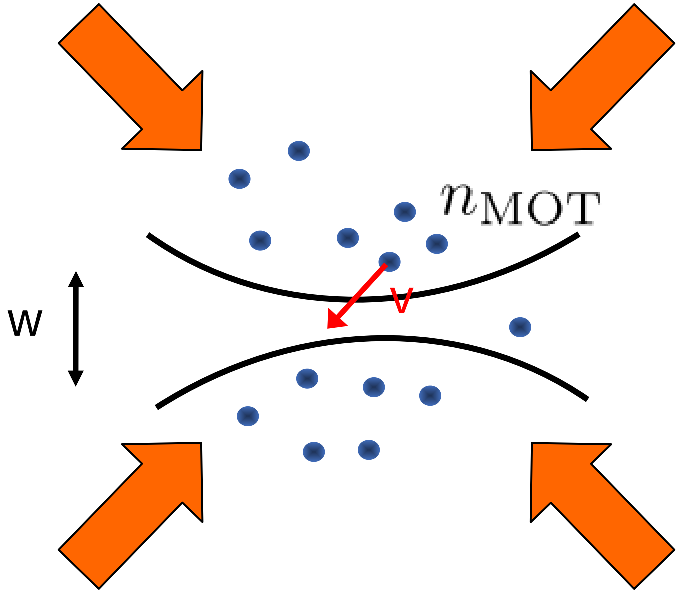
Loading rate (~ density of the MOT) = R



$$R \sim n_{\mathrm{MOT}}\, w^2\, v$$

Loading a tweezer from a MOT

Loading rate (~ density of the MOT) = R

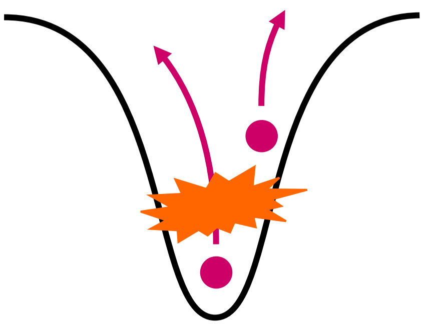


$$R \sim n_{\mathrm{MOT}}\, w^2\, v$$

Two-body loss rate in the trap

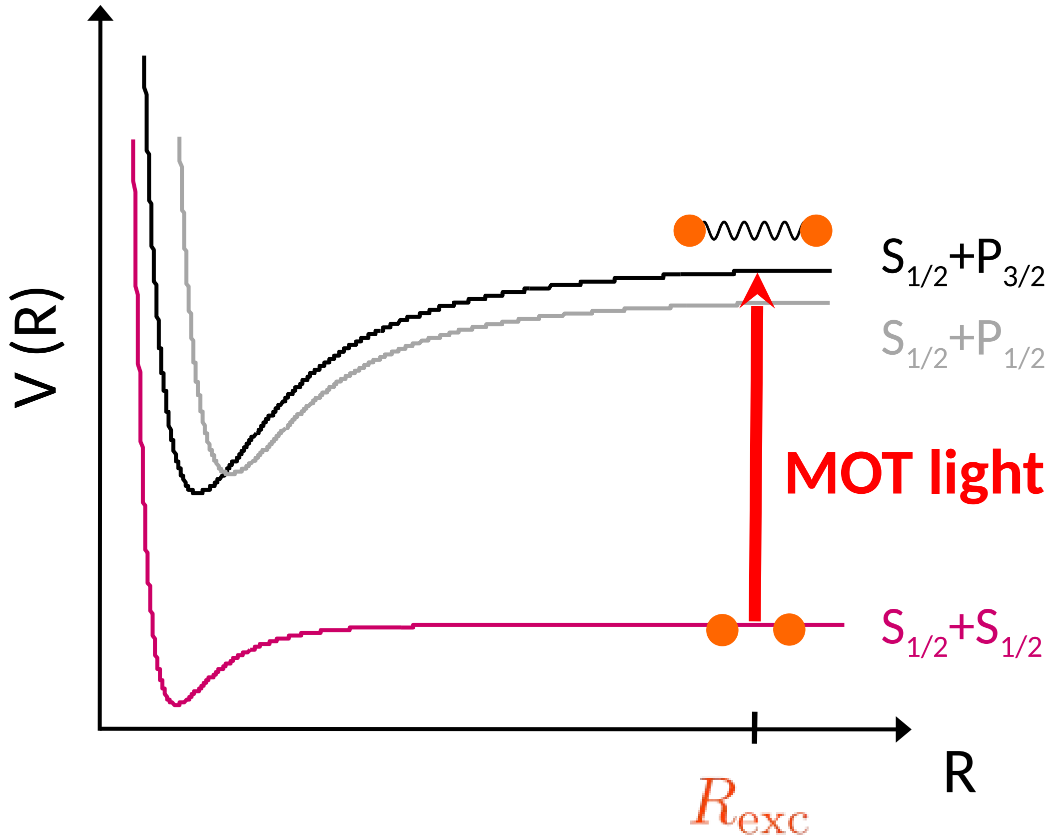
$$2\,\frac{\beta}{V}\,\frac{N(N-1)}{2}$$

V ~ trap size



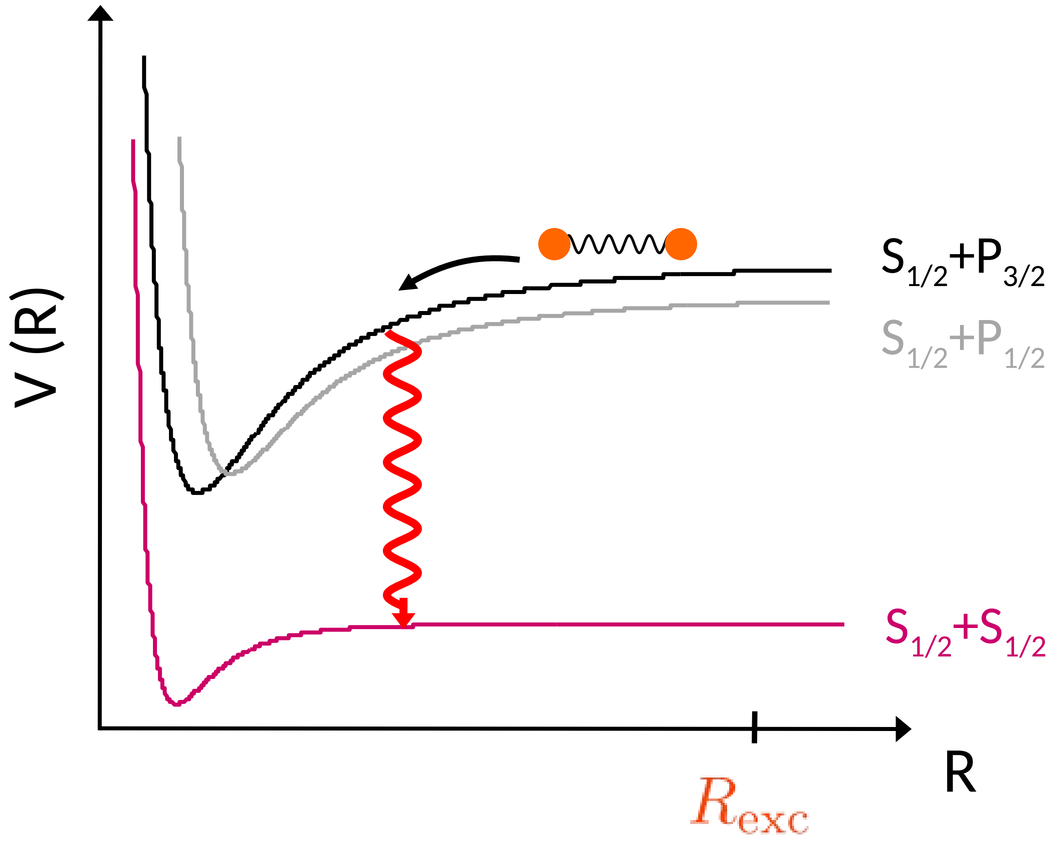
Light-assisted collision

Light-assisted collisions (radiative escape)



A. Gallagher & Pritchard PRL **63**, 957 (1989)
A. Fuhrmanek, PRA **85**, 062708 (2012)

Light-assisted collisions (radiative escape)



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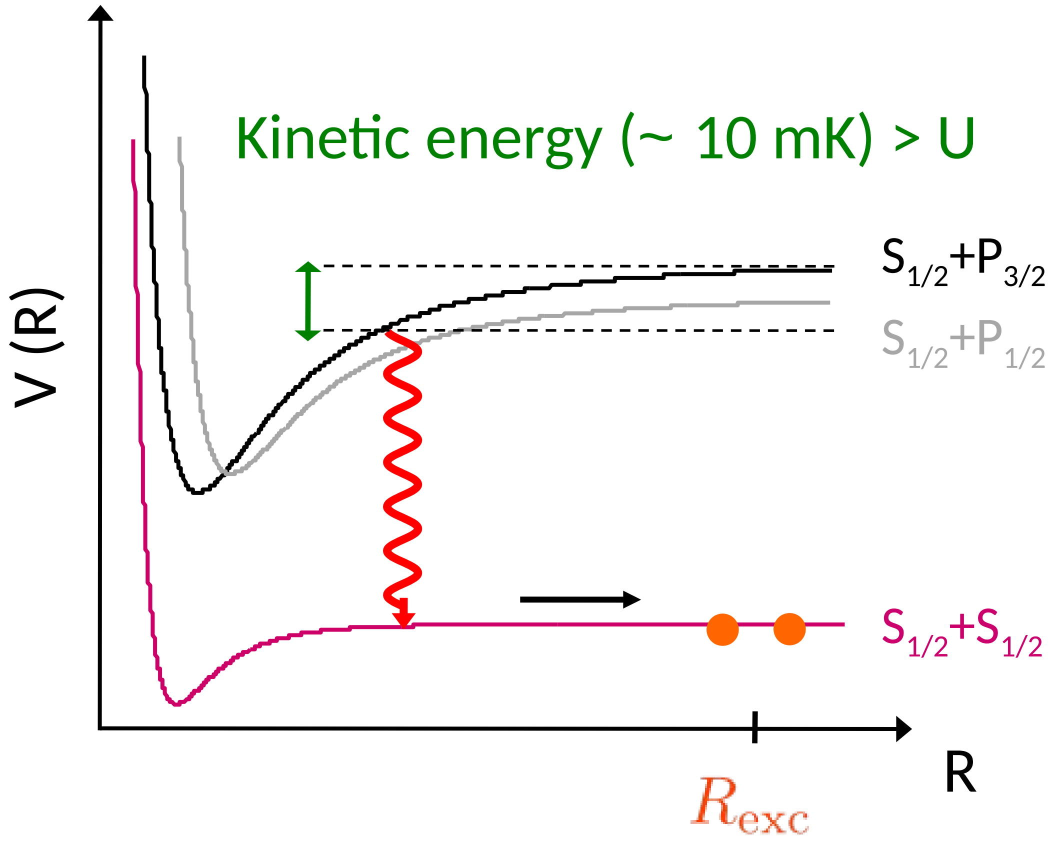
Light-assisted collisions (radiative escape)



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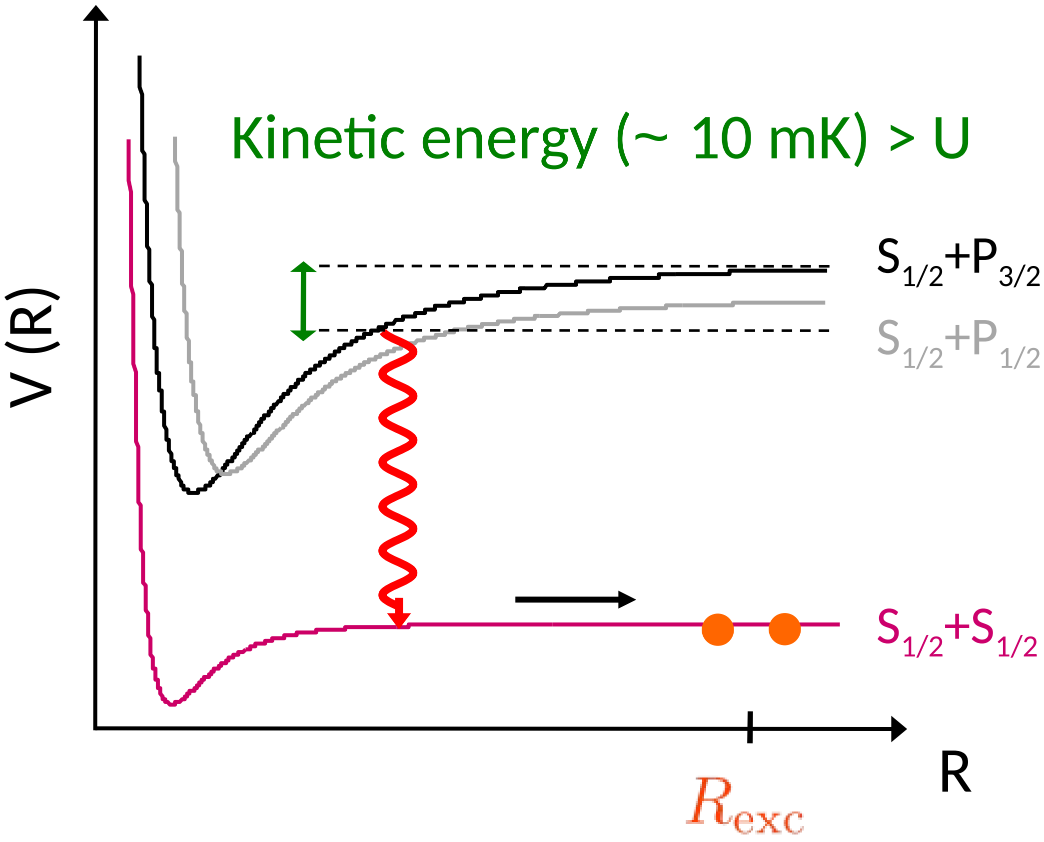
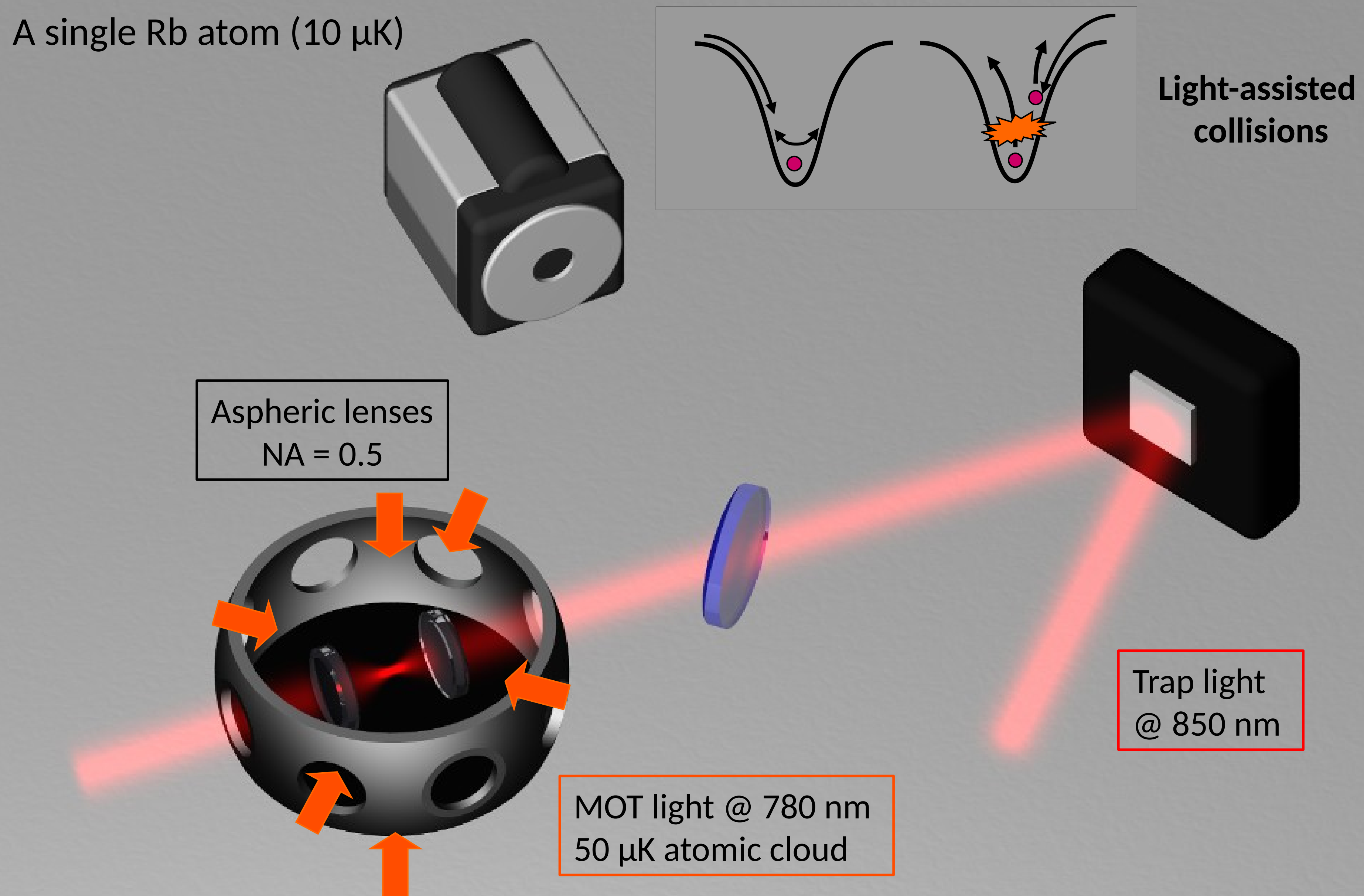
Light-assisted collisions (radiative escape)



2 atoms remain in the trap less than $\frac{V}{\beta} \sim 100\ \mu\text{sec}$

A. Gallagher & Pritchard PRL **63**, 957 (1989)
A. Fuhrmanek, PRA **85**, 062708 (2012)

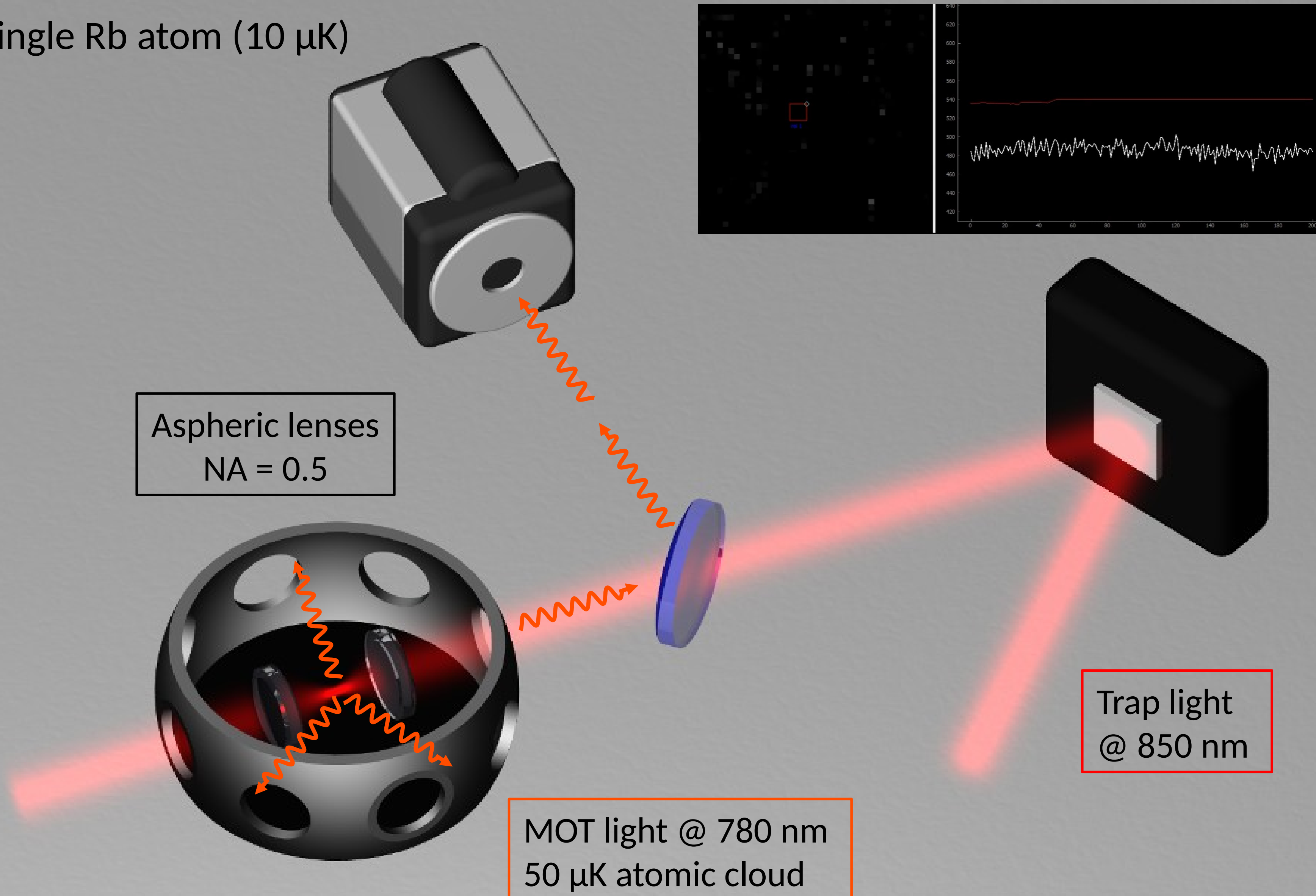
Individual atoms in optical tweezers



Schlosser *et al.*, *Nature* **411**, 1024 (2001)

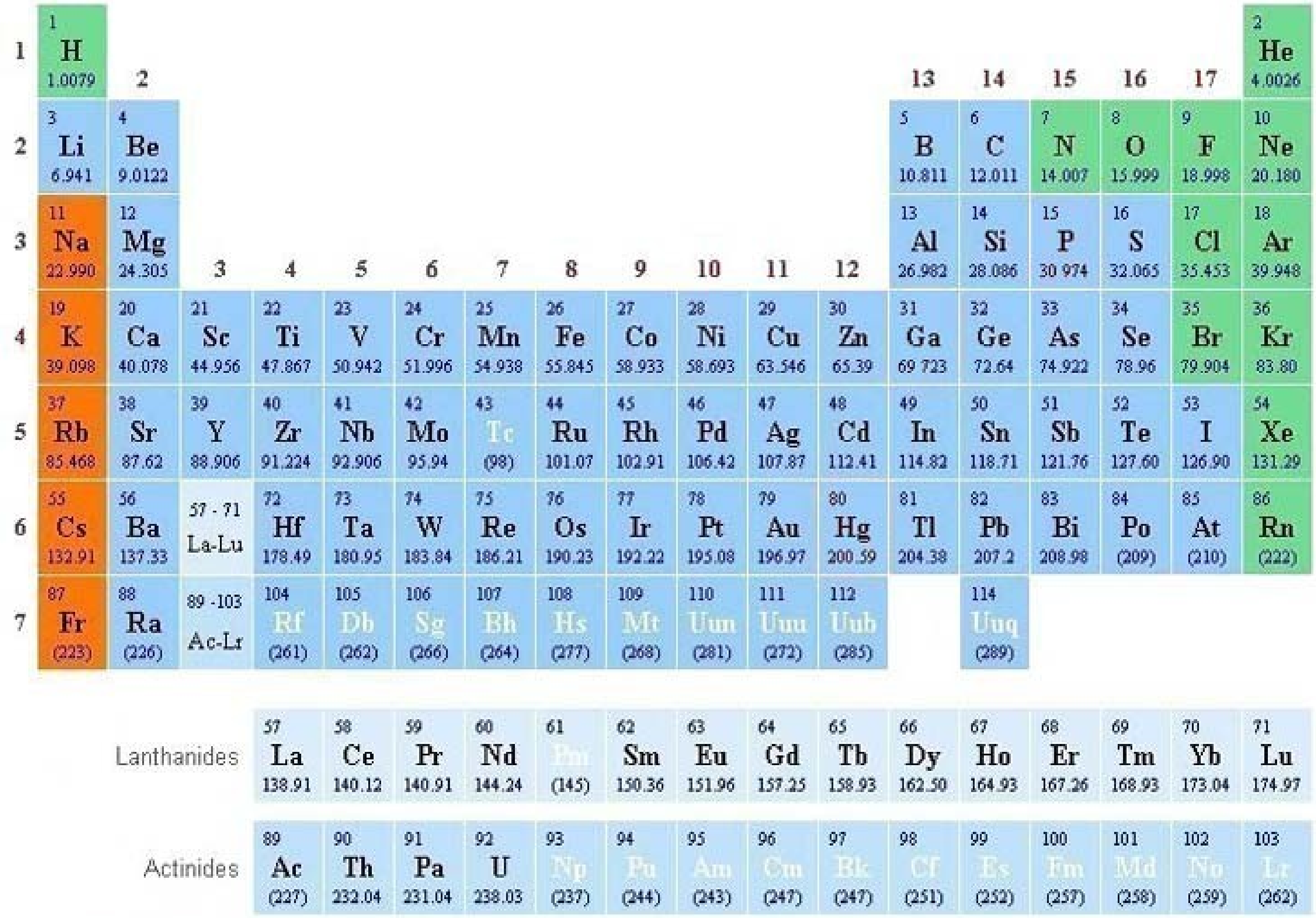
Individual atoms in optical tweezers

A single Rb atom (10 µK)



Schlosser *et al.*, *Nature* **411**, 1024 (2001)

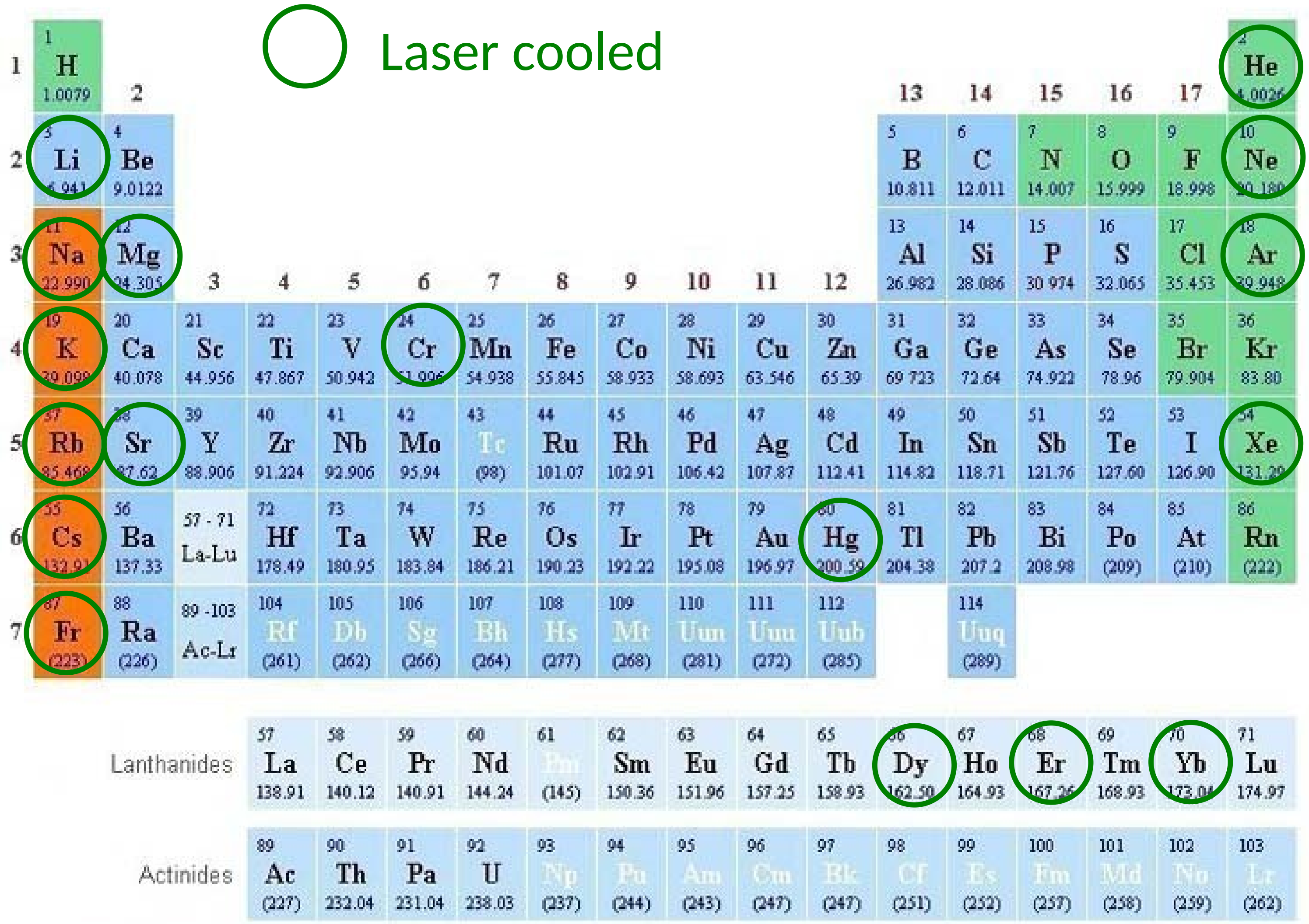
Which atoms?



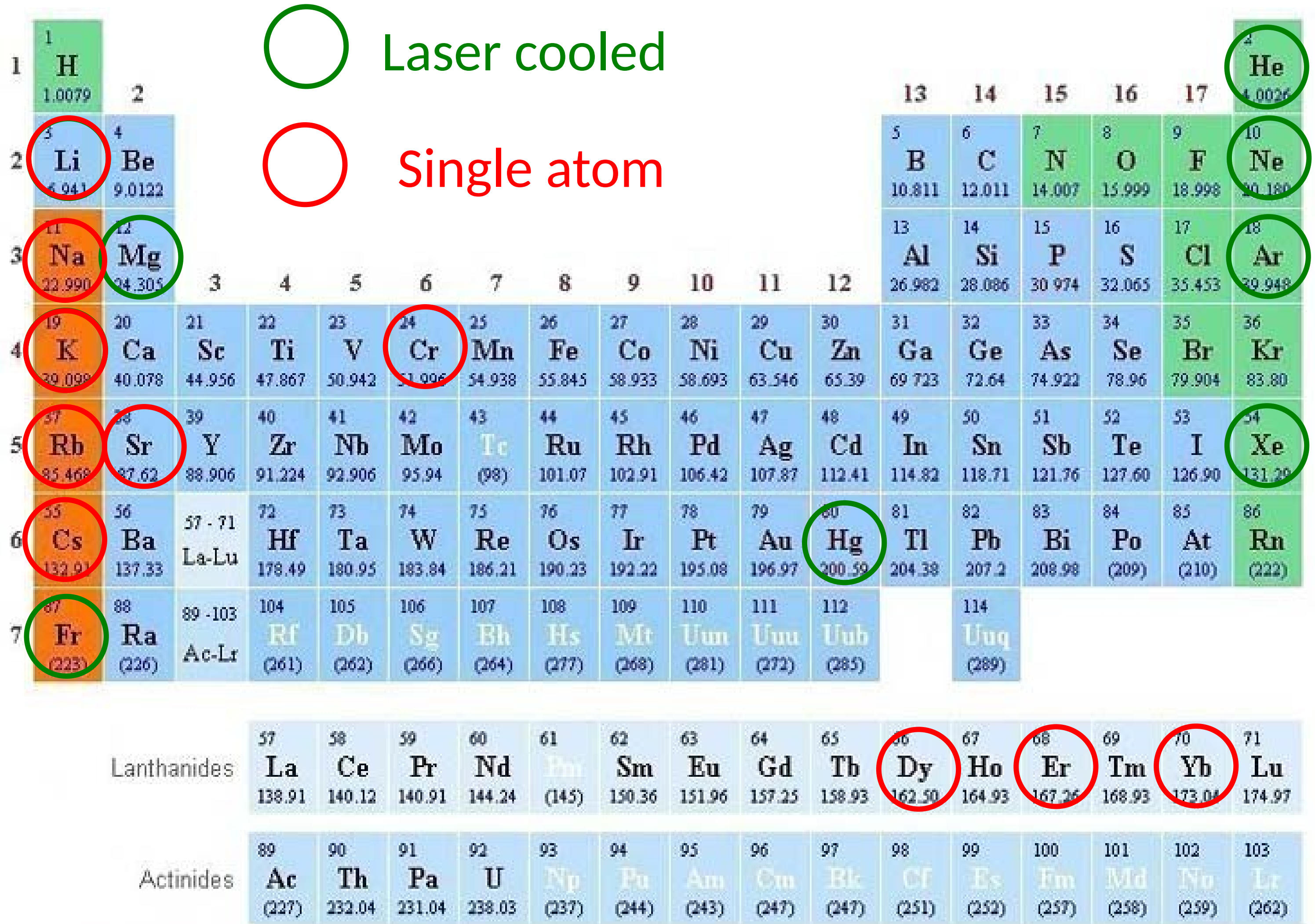
		2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	
1	1 H 1.0079																	2 He 4.0026
2	3 Li 6.941	4 Be 9.0122											5 B 10.811	6 C 12.011	7 N 14.007	8 O 15.999	9 F 18.998	10 Ne 20.180
3	11 Na 22.990	12 Mg 24.305											13 Al 26.982	14 Si 28.086	15 P 30.974	16 S 32.065	17 Cl 35.453	18 Ar 39.948
4	19 K 39.098	20 Ca 40.078	21 Sc 44.956	22 Ti 47.867	23 V 50.942	24 Cr 51.996	25 Mn 54.938	26 Fe 55.845	27 Co 58.933	28 Ni 58.693	29 Cu 63.546	30 Zn 65.39	31 Ga 69.723	32 Ge 72.64	33 As 74.922	34 Se 78.96	35 Br 79.904	36 Kr 83.80
5	37 Rb 85.468	38 Sr 87.62	39 Y 88.906	40 Zr 91.224	41 Nb 92.906	42 Mo 95.94	43 Tc (98)	44 Ru 101.07	45 Rh 102.91	46 Pd 106.42	47 Ag 107.87	48 Cd 112.41	49 In 114.82	50 Sn 118.71	51 Sb 121.76	52 Te 127.60	53 I 126.90	54 Xe 131.29
6	55 Cs 132.91	56 Ba 137.33	57 - 71 La-Lu	72 Hf 178.49	73 Ta 180.95	74 W 183.84	75 Re 186.21	76 Os 190.23	77 Ir 192.22	78 Pt 195.08	79 Au 196.97	80 Hg 200.59	81 Tl 204.38	82 Pb 207.2	83 Bi 208.98	84 Po (209)	85 At (210)	86 Rn (222)
7	87 Fr (223)	88 Ra (226)	89 -103 Ac-Lr	104 Rf (261)	105 Db (262)	106 Sg (266)	107 Bh (264)	108 Hs (277)	109 Mt (268)	110 Uun (281)	111 Uuu (272)	112 Uub (285)		114 Uuq (289)				

Lanthanides	57 La 138.91	58 Ce 140.12	59 Pr 140.91	60 Nd 144.24	61 Pm (145)	62 Sm 150.36	63 Eu 151.96	64 Gd 157.25	65 Tb 158.93	66 Dy 162.50	67 Ho 164.93	68 Er 167.26	69 Tm 168.93	70 Yb 173.04	71 Lu 174.97
Actinides	89 Ac (227)	90 Th 232.04	91 Pa 231.04	92 U 238.03	93 Np (237)	94 Pu (244)	95 Am (243)	96 Cm (247)	97 Bk (247)	98 Cf (251)	99 Es (252)	100 Fm (257)	101 Md (258)	102 No (259)	103 Lr (262)

Which atoms?



Which atoms?



Laser cooled
Single atom
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17
1 H 1.0079
2 He 4.0026
3 Li 6.941
4 Be 9.0122
5 B 10.811
6 C 12.011
7 N 14.007
8 O 15.999
9 F 18.998
10 Ne 20.180
11 Na 22.990
12 Mg 24.305
13 Al 26.982
14 Si 28.086
15 P 30.974
16 S 32.065
17 Cl 35.453
18 Ar 39.948
19 K 39.098
20 Ca 40.078
21 Sc 44.956
22 Ti 47.867
23 V 50.942
24 Cr 51.996
25 Mn 54.938
26 Fe 55.845
27 Co 58.933
28 Ni 58.693
29 Cu 63.546
30 Zn 65.39
31 Ga 69.723
32 Ge 72.64
33 As 74.922
34 Se 78.96
35 Br 79.904
36 Kr 83.80
37 Rb 85.468
38 Sr 87.62
39 Y 88.906
40 Zr 91.224
41 Nb 92.906
42 Mo 95.94
43 Tc (98)
44 Ru 101.07
45 Rh 102.91
46 Pd 106.42
47 Ag 107.87
48 Cd 112.41
49 In 114.82
50 Sn 118.71
51 Sb 121.76
52 Te 127.60
53 I 126.90
54 Xe 131.29
55 Cs 132.91
56 Ba 137.33
57 - 71 La-Lu
72 Hf 178.49
73 Ta 180.95
74 W 183.84
75 Re 186.21
76 Os 190.23
77 Ir 192.22
78 Pt 195.08
79 Au 196.97
80 Hg 200.59
81 Tl 204.38
82 Pb 207.2
83 Bi 208.98
84 Po (209)
85 At (210)
86 Rn (222)
87 Fr (223)
88 Ra (226)
89 -103 Ac-Lr
104 Rf (261)
105 Db (262)
106 Sg (266)
107 Bh (264)
108 Hs (277)
109 Mt (268)
110 Uun (281)
111 Uuu (272)
112 Uub (285)
114 Uuq (289)
Lanthanides
57 La 138.91
58 Ce 140.12
59 Pr 140.91
60 Nd 144.24
61 Pm (145)
62 Sm 150.36
63 Eu 151.96
64 Gd 157.25
65 Tb 158.93
66 Dy 162.50
67 Ho 164.93
68 Er 167.26
69 Tm 168.93
70 Yb 173.04
71 Lu 174.97
Actinides
89 Ac (227)
90 Th 232.04
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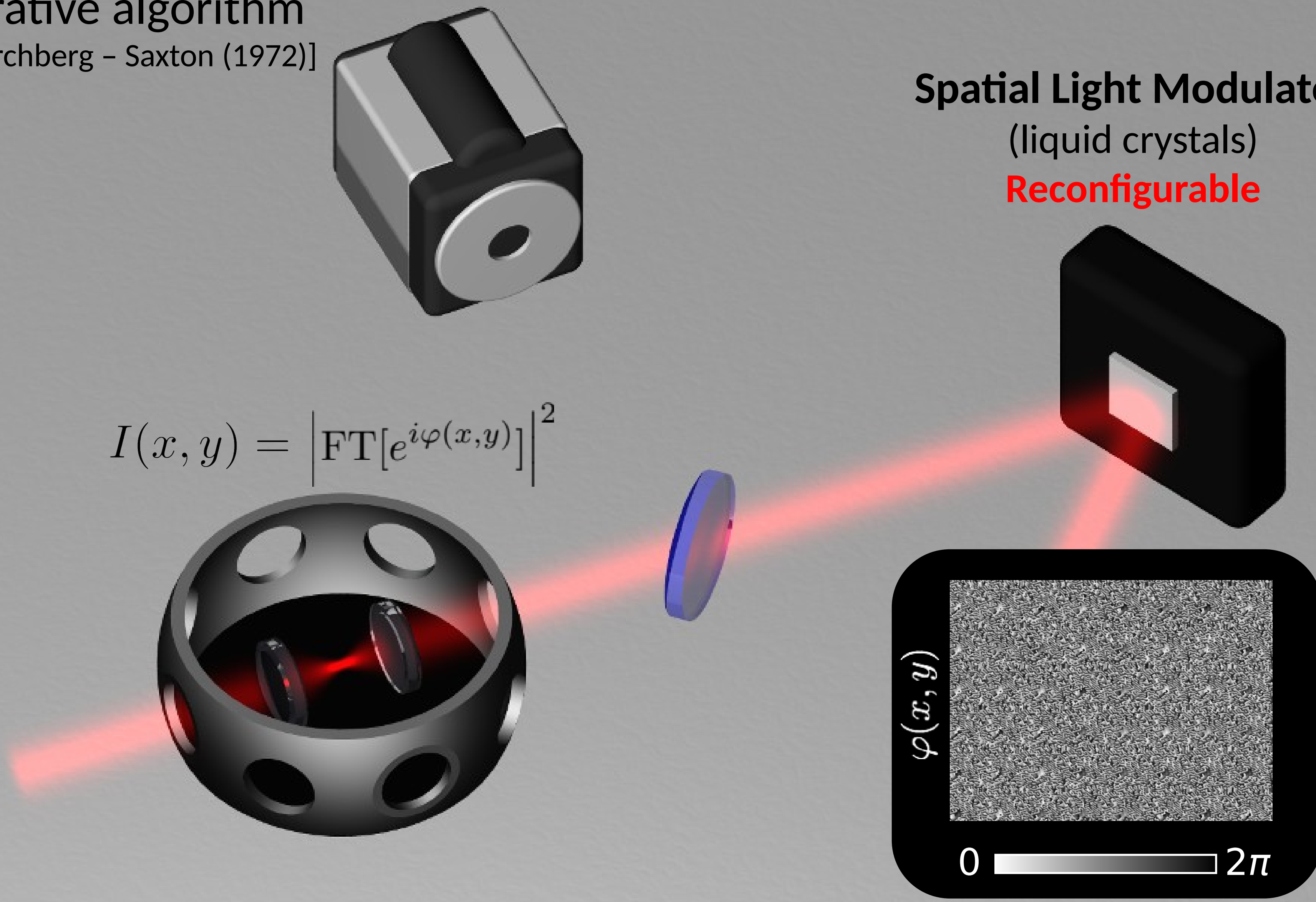
93 Np (237)
94 Pu (244)
95 Am (243)
96 Cm (247)
97 Bk (247)
98 Cf (251)
99 Es (252)
100 Fm (257)
101 Md (258)
102 No (259)
103 Lr (262)

Individual atoms in optical tweezers

Iterative algorithm
[Gerchberg – Saxton (1972)]

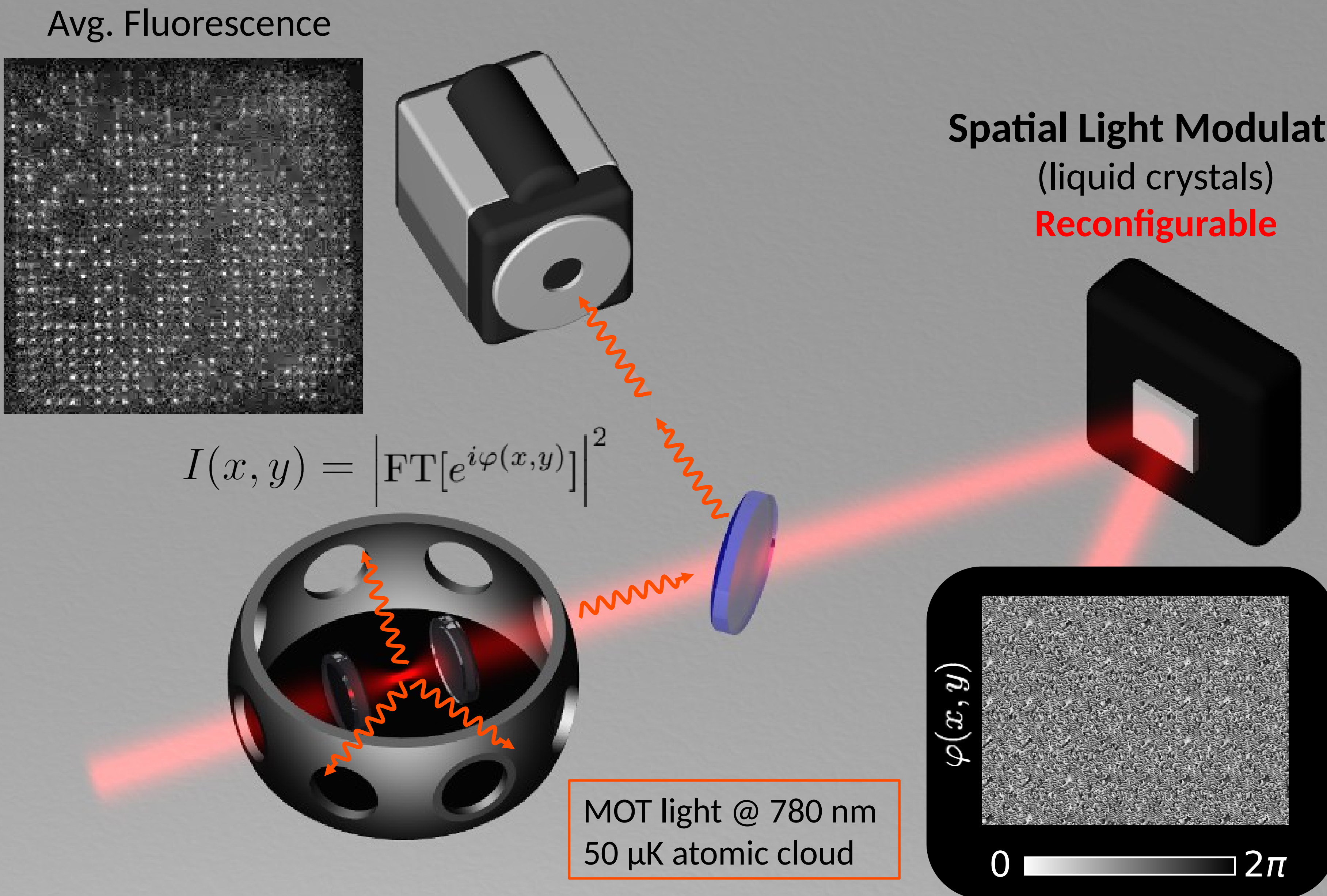
Spatial Light Modulator
(liquid crystals)
Reconfigurable

$$I(x,y) = \left|\mathrm{FT}[e^{i\varphi(x,y)}]\right|^2$$



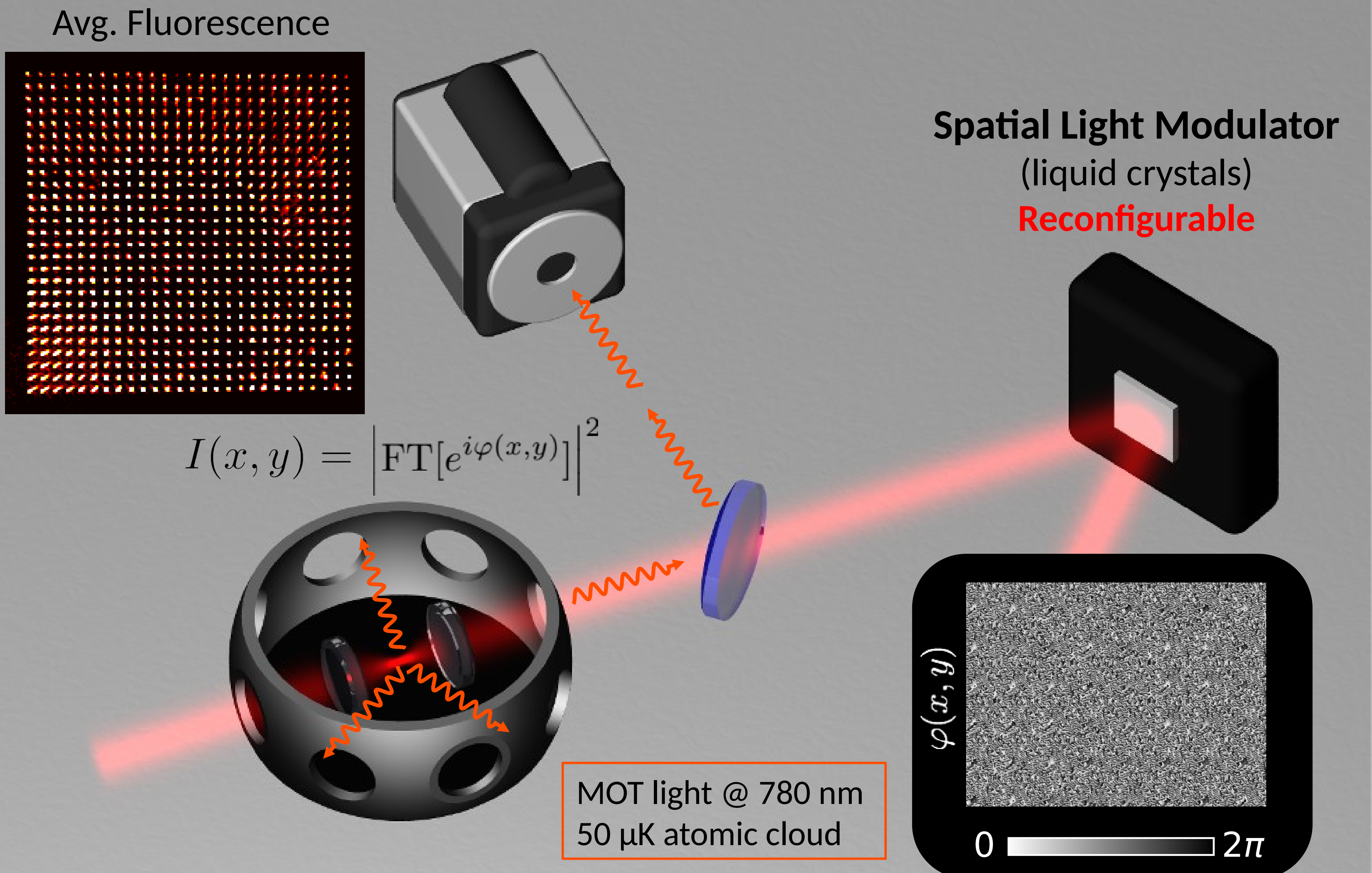
Nogrette *et al.*, *PRX* **4**, 021034 (2014)

Individual atoms in optical tweezers



Nogrette *et al.*, *PRX* **4**, 021034 (2014)

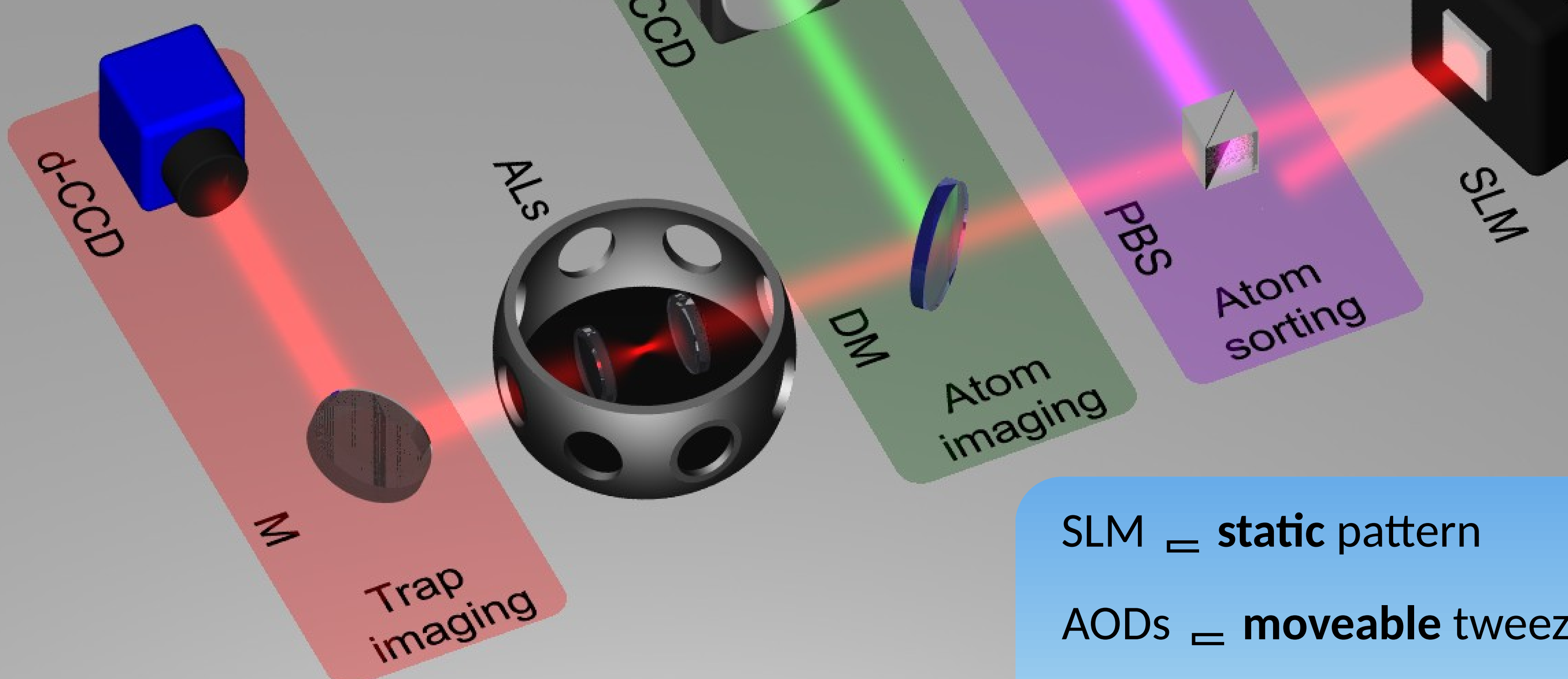
Individual atoms in optical tweezers



Nogrette *et al.*, *PRX* **4**, 021034 (2014)

Assembled arrays of individual atoms

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



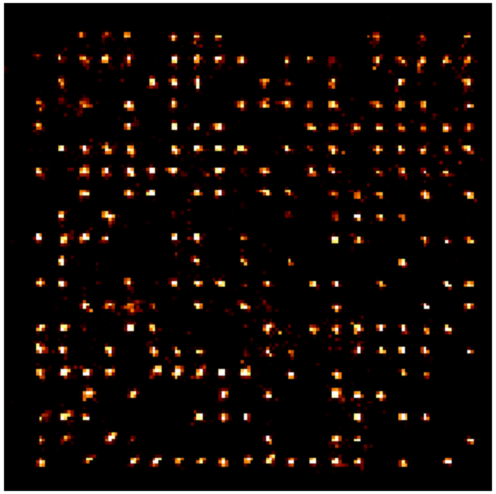
SLM = **static** pattern

AODs = **moveable** tweezers

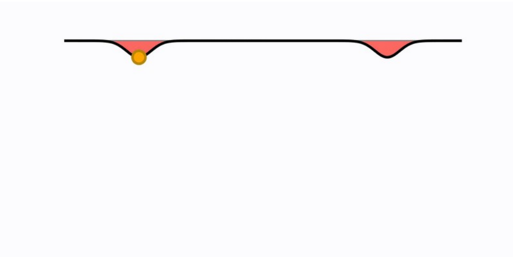
Timescale : 300 μs / move

Assembled arrays of individual atoms

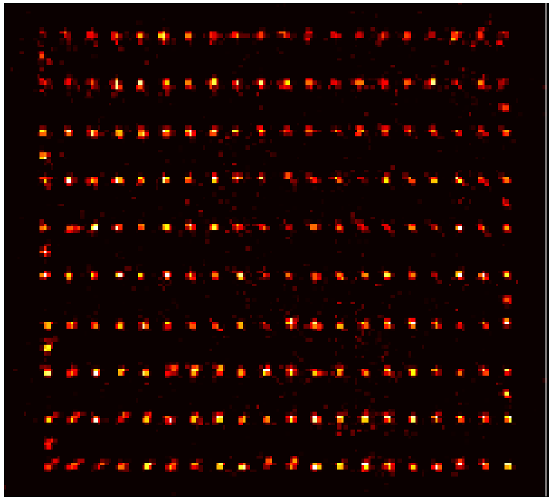
Initial configuration



Assembling process



Assembled configuration



~100 μm

Solution: sorting atom in the arrays

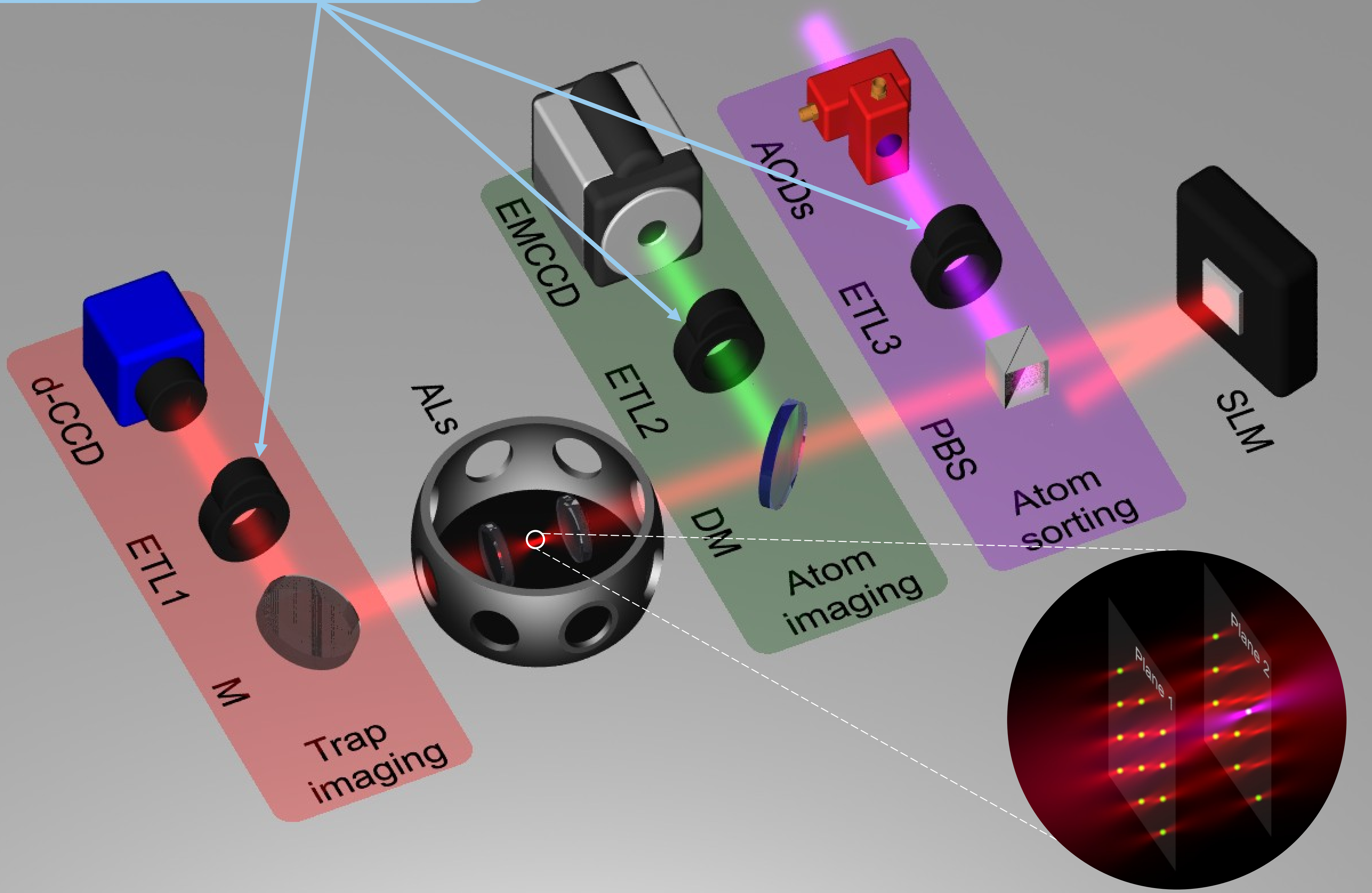
Miroshnychenko, Nature **442**, 151 (2006)

Related: Endres *et al.*, Science **354**,1024 (2016)
Kim *et al.*, Nat. Comm. **7**, 13317 (2016)

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

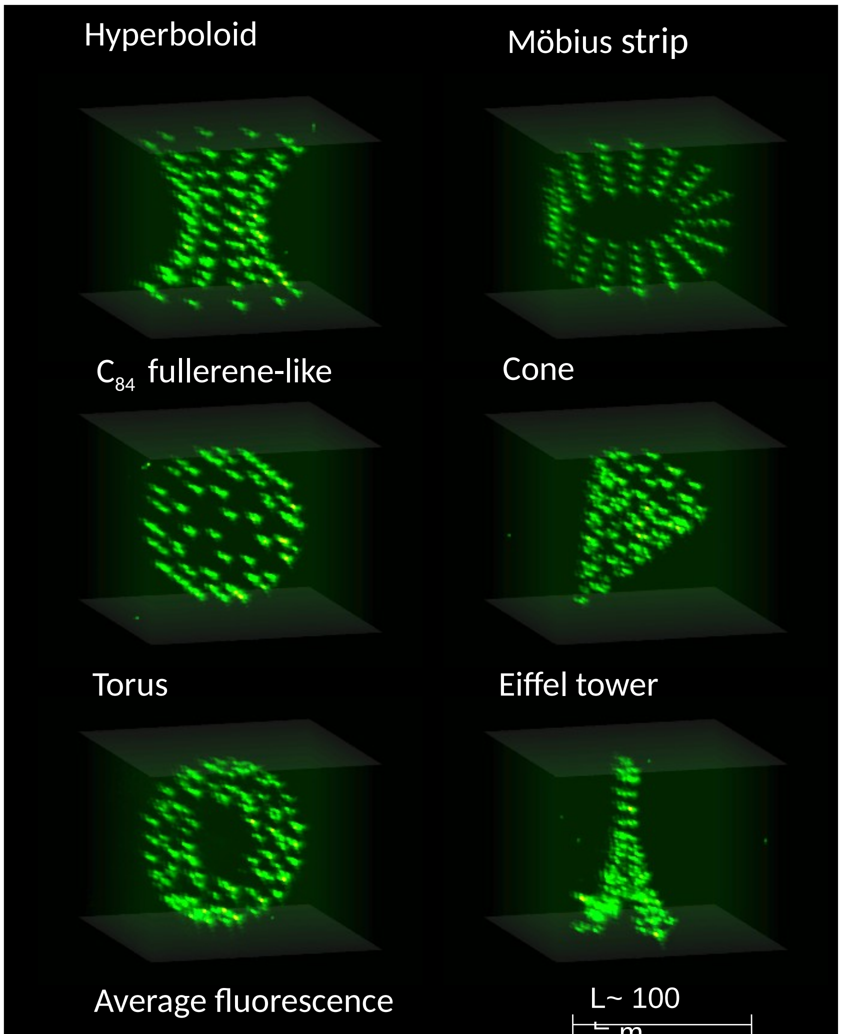
What about 3D arrays?

Electrically tunable lenses

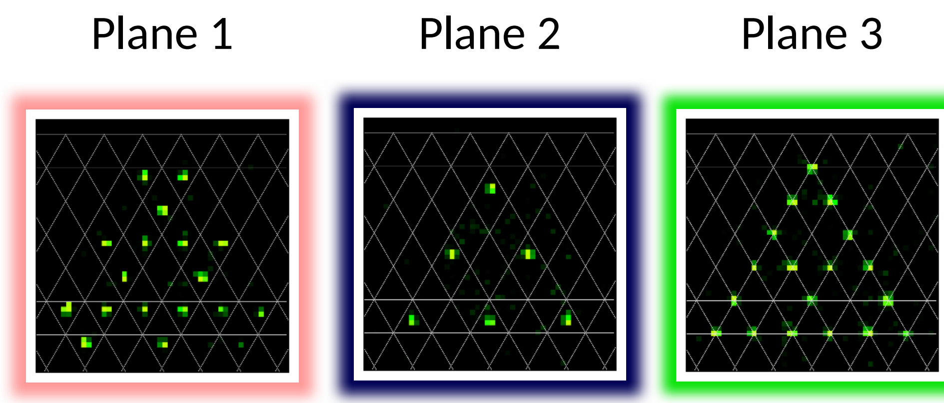


It also works in 3D!

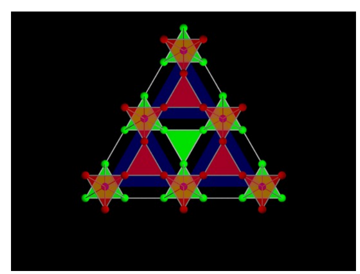
- Holographic traps (with SLM) also works in 3D
- Imaging in 3D with a single EMCCD camera
  - fast tunable lens for multi-plane imaging



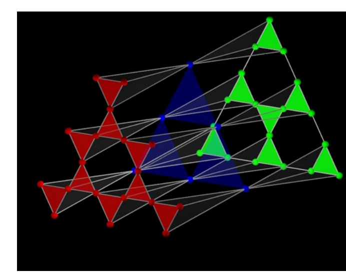
Assembled Pyrochlore lattice



Front view



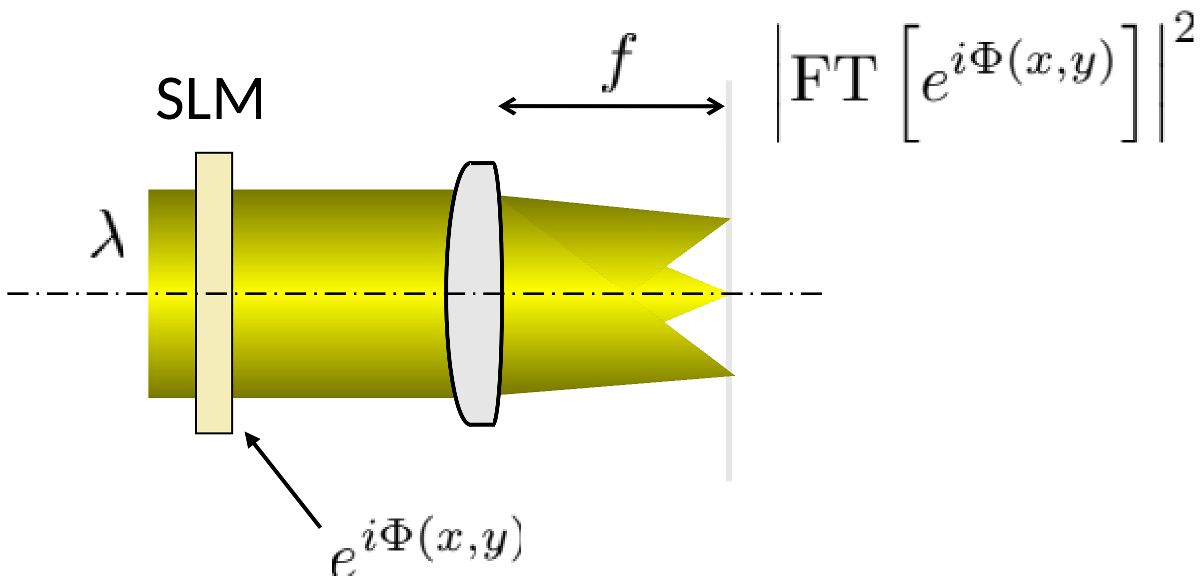
Side view



Barredo *et al.*, Nature **561**, 79 (2018)

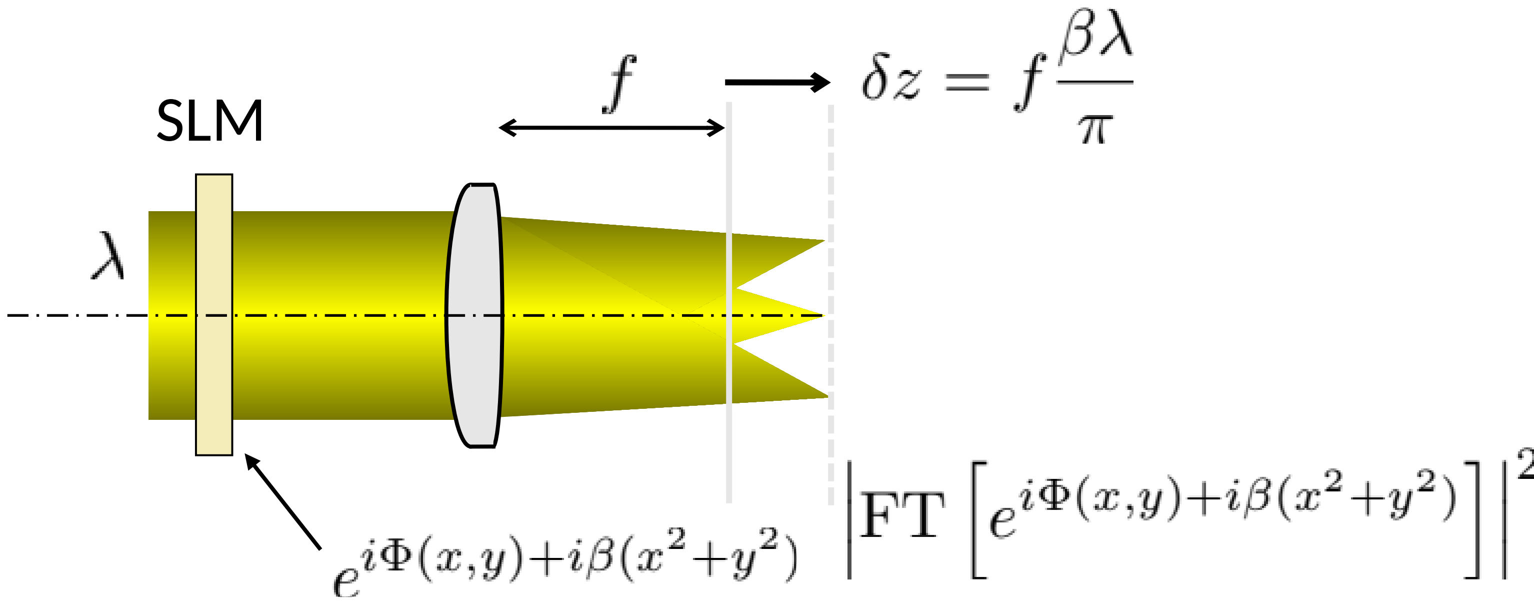
3D holographic arrays

Di Leonardo, Optics Express **15**, 1913 (2007)



3D holographic arrays

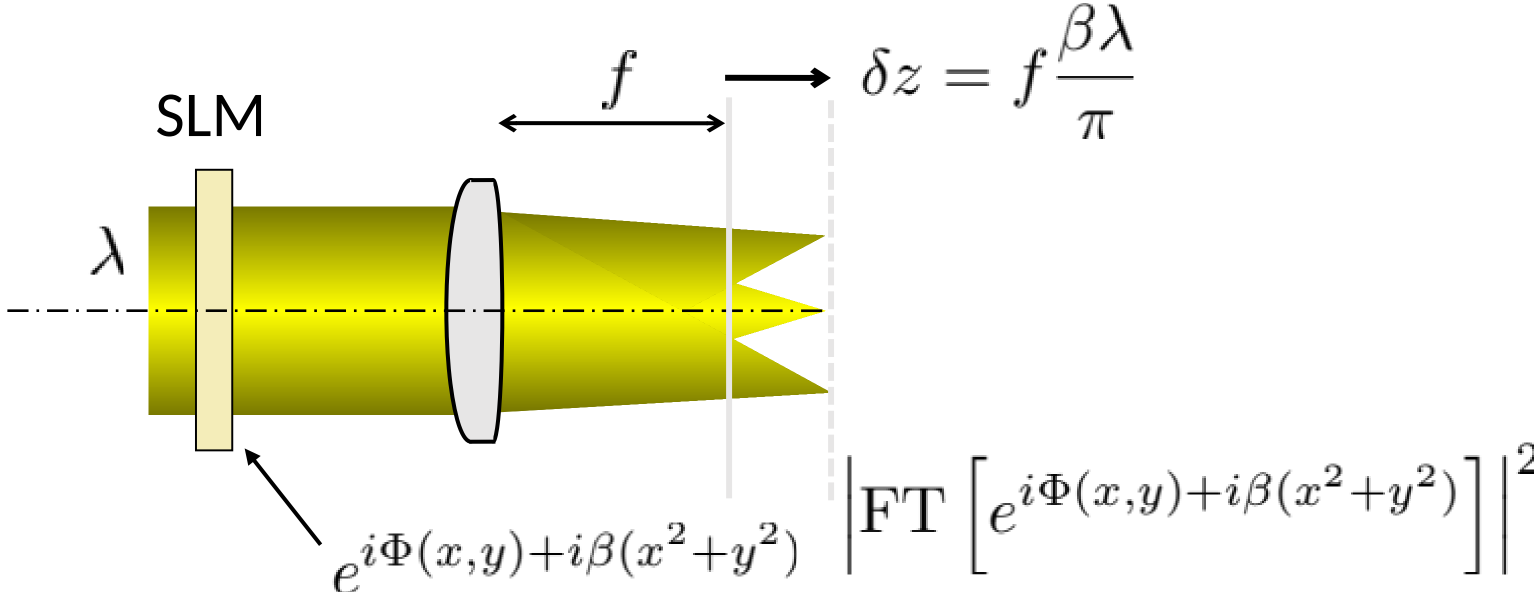
Di Leonardo, Optics Express **15**, 1913 (2007)



Quadratic phase = **lensing**

3D holographic arrays

Di Leonardo, Optics Express **15**, 1913 (2007)



Quadratic phase = **lensing**

Approximate solution for multi-planes: use superposition principle

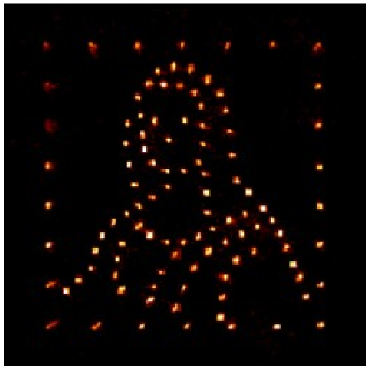
$$\Phi(x,y) = \arg[e^{i\Phi_1(x,y)} + e^{i\Phi_2(x,y)} + \ldots]$$

Plane 1 Plane 2

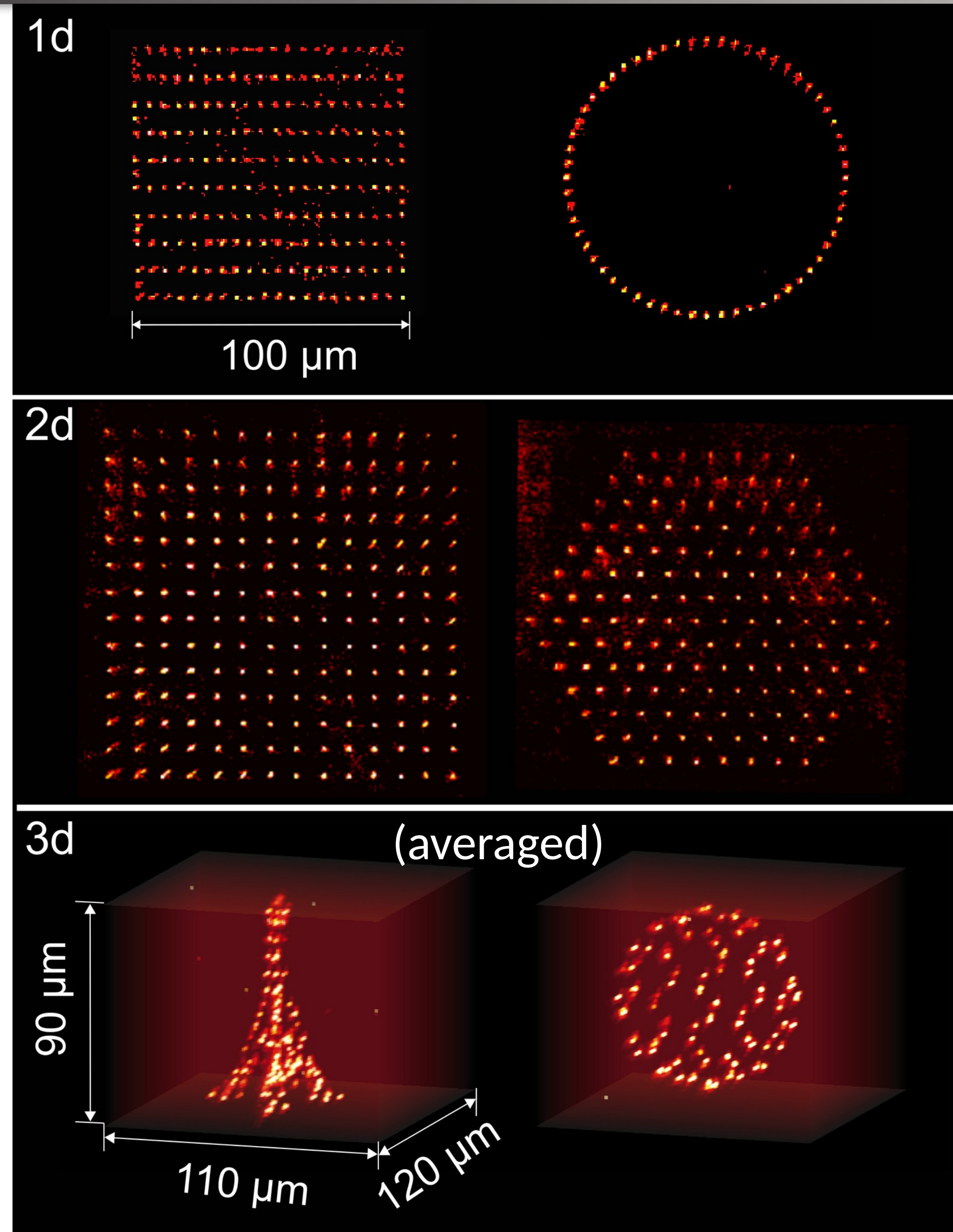
Assembled arrays of individual atoms

New assembler algorithms:

Schymik *et al.*, PRA, **102**, 063107 (2020)



L. da Vinci



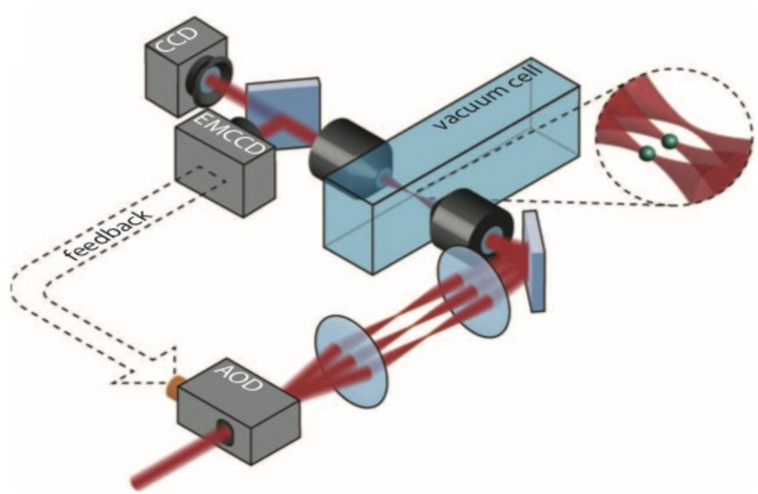
For N = 100 atoms:

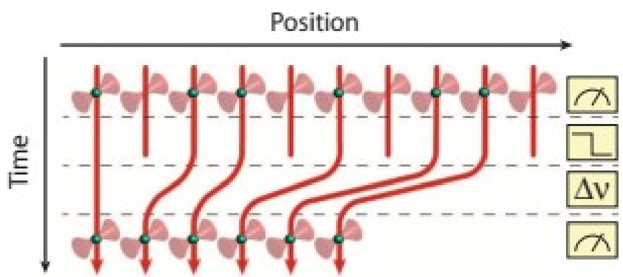
Filling fraction > 99 %

Probability of defect free shots ~ 40 %

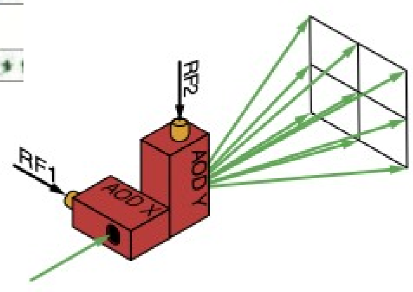
Assembled arrays in the world

Lukin (Harvard), 2016



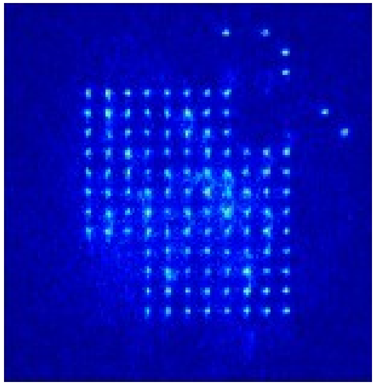


Rb



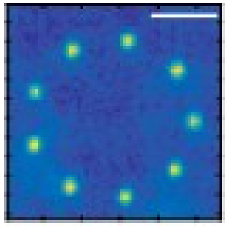
Birkl (Germany)

2D

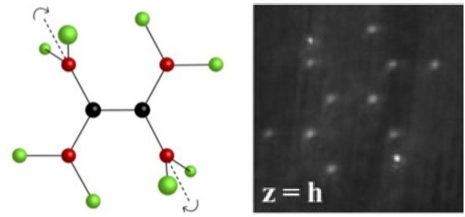


Ahn (Korea)

2D

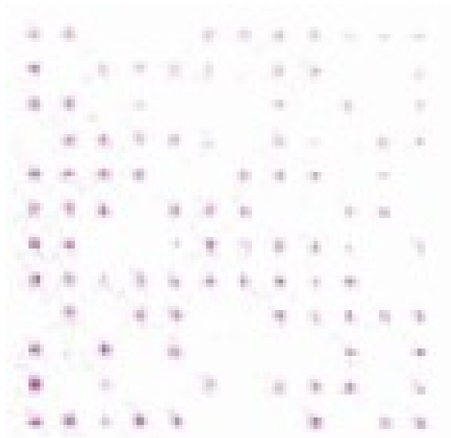


3D

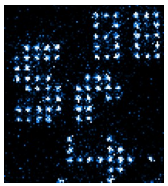


Sr

Yb



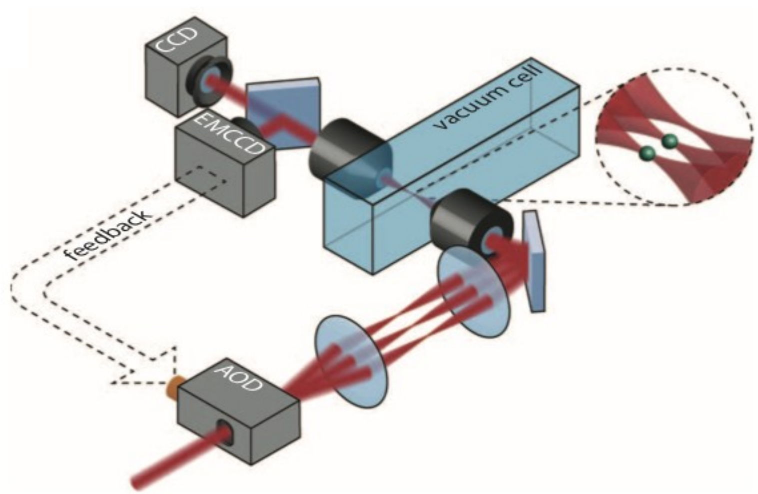
Endres (Caltech)
Kauffman (JILA)
2018

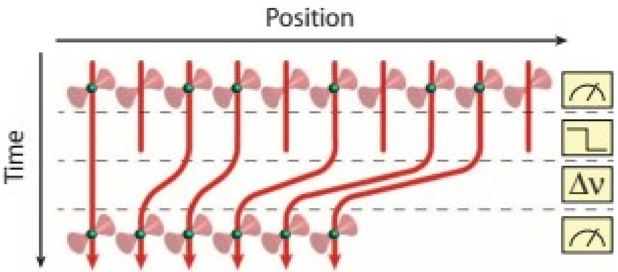


Thompson (Princeton)
2018

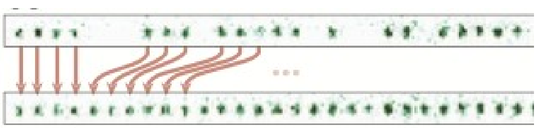
Assembled arrays in the world

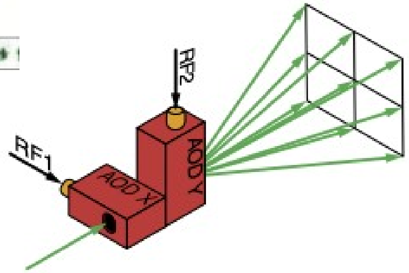
Lukin (Harvard), 2016





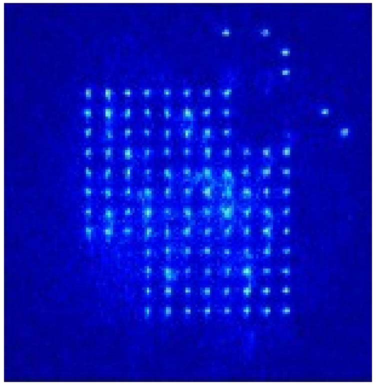
Rb





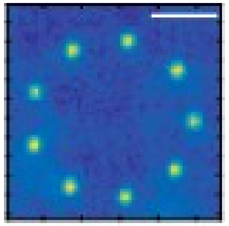
Birkl (Germany)

2D

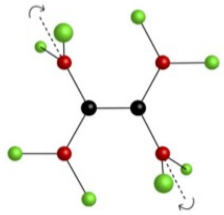


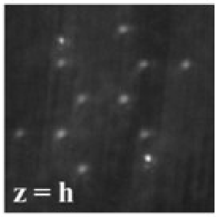
Ahn (Korea)

2D



3D





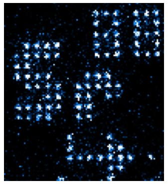
Sr

Yb

And many more on the way:

Bonn, Yale, Columbia, Tokyo, Argonne, UIUC, Amsterdam, Durham, MPQ (4), Pasqal, Atom Computing, ETH, Munich, Hamburg…

Endres (Caltech)
Kauffman (JILA)
2018



Thompson (Princeton)
2018

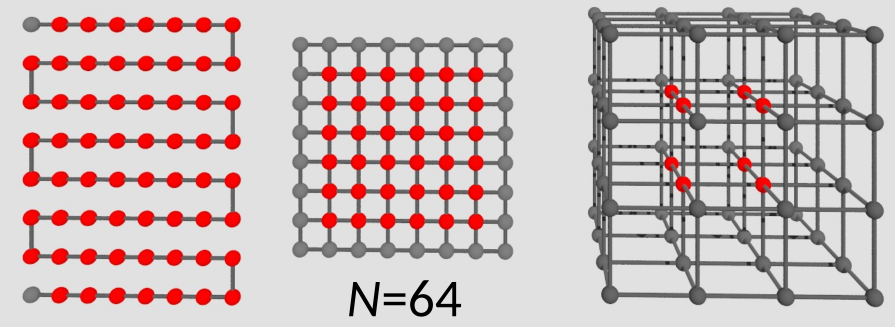
Towards more atoms: arrays in a cryostat

Why larger arrays?

Towards more atoms: arrays in a cryostat

Why larger arrays?

Avoid edge effects…



Towards more atoms: arrays in a cryostat

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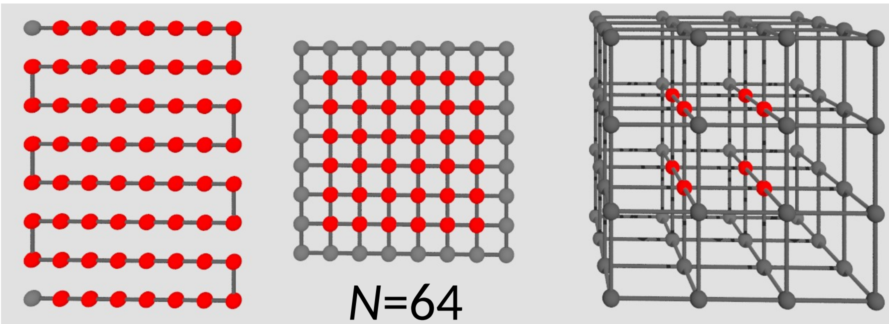
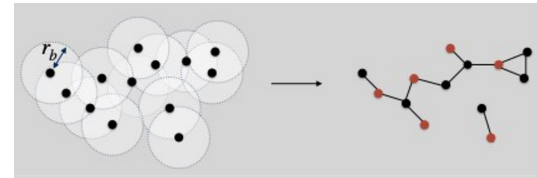


Optimization problems *N* > 1000

Graph problems (MIS)

Lukin & Pichler ,
Ahn, Pasqal, Ayral…



Towards more atoms: arrays in a cryostat

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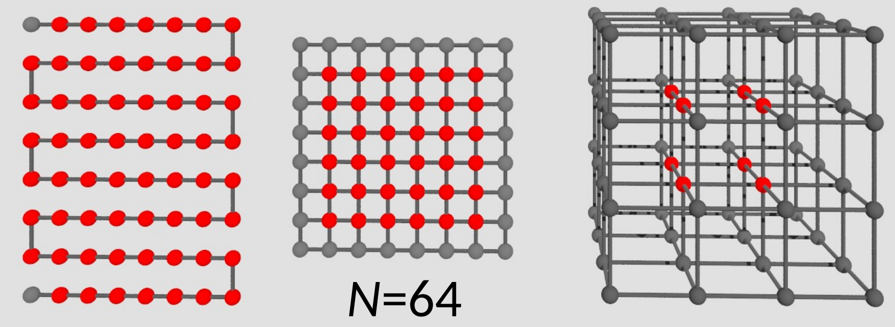

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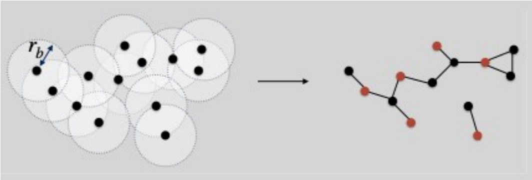


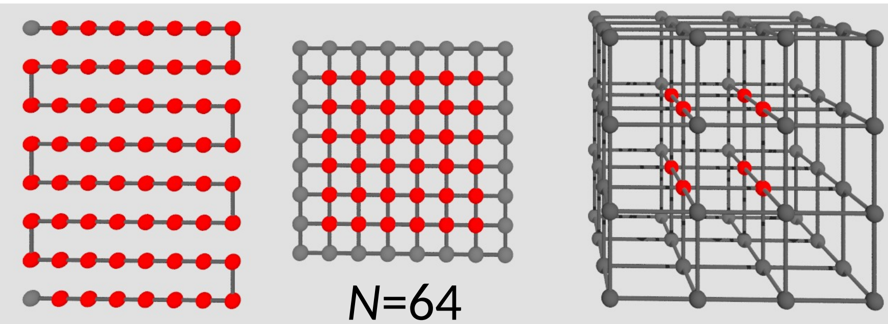
Alexandre Dauphine

Next week!

Towards more atoms: arrays in a cryostat

Why larger arrays?

Avoid edge effects…



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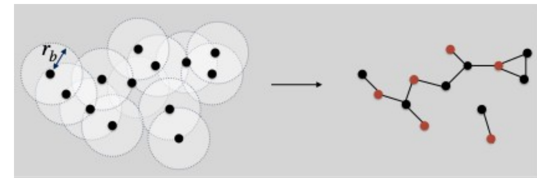


Quantum error correction

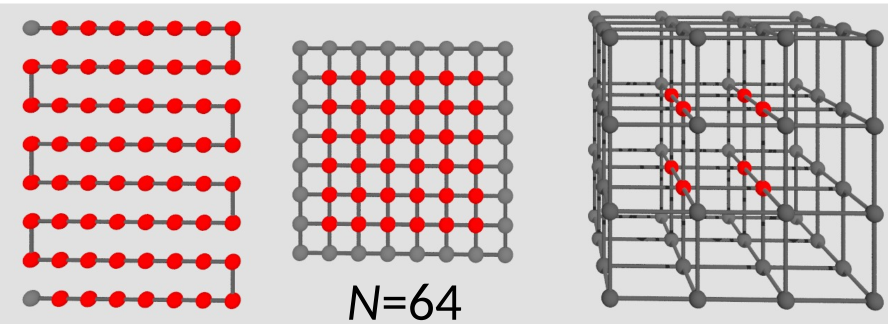
~ 100 phys. qbits for 1 logical qbit

Lifetime: $\tau_1 \rightarrow \tau_N = \tau_1/N$ atom losses + detection errors

Towards more atoms: arrays in a cryostat

Why larger arrays?

Avoid edge effects…



Optimization problems *N* > 1000

Graph problems (MIS)

Lukin & Pichler ,
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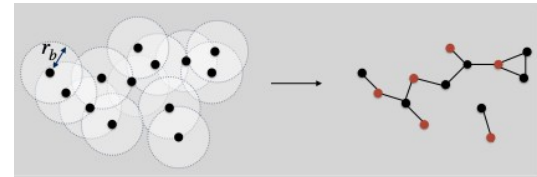

Quantum error correction

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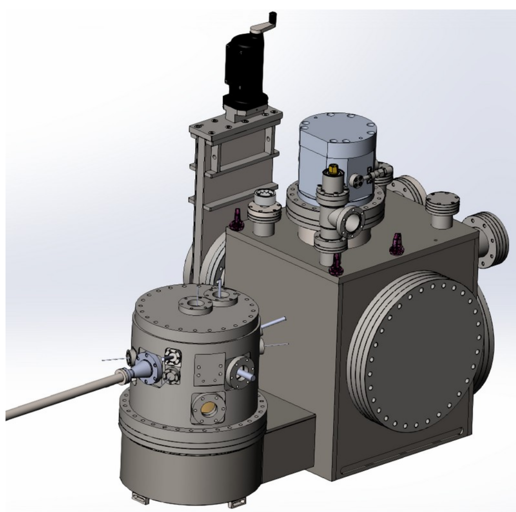
Lifetime: $\tau_1 \rightarrow \tau_N = \tau_1/N$ ⇒ atom losses + detection errors

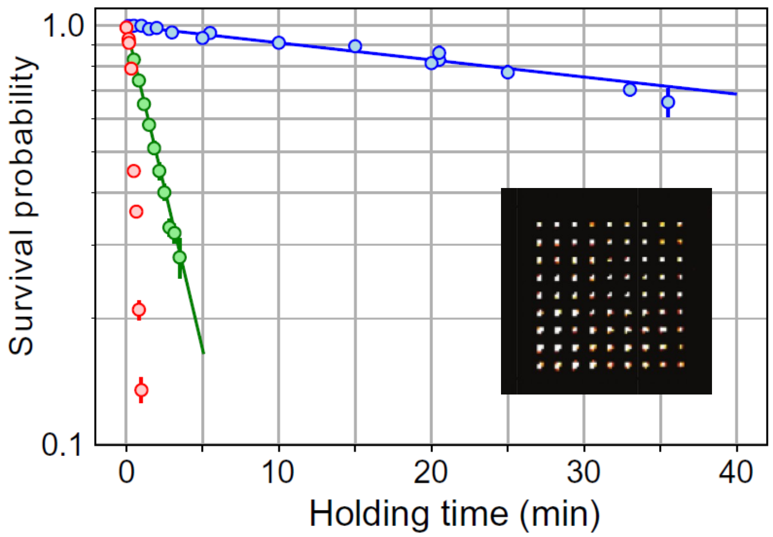
MYCRYOFIRM
CRYOGENIC SOLUTIONS

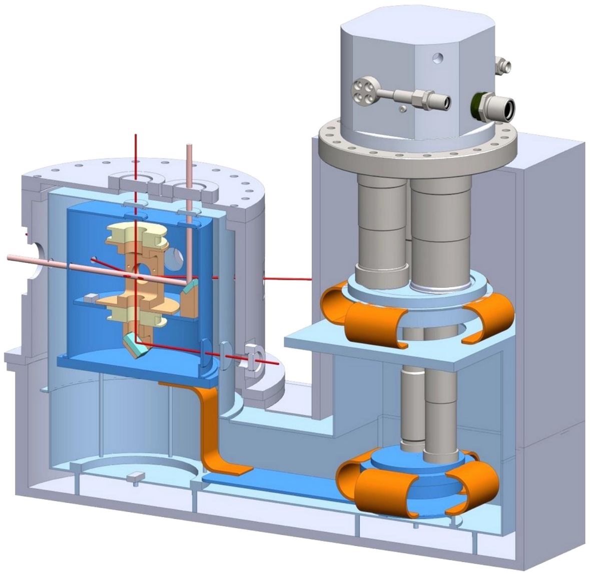


Development of a 4K, UHV compatible closed-cycle cryostat ⇒ "vacuum ~ 0"

K.N. Schymik, Phys. Rev. Applied (2021)

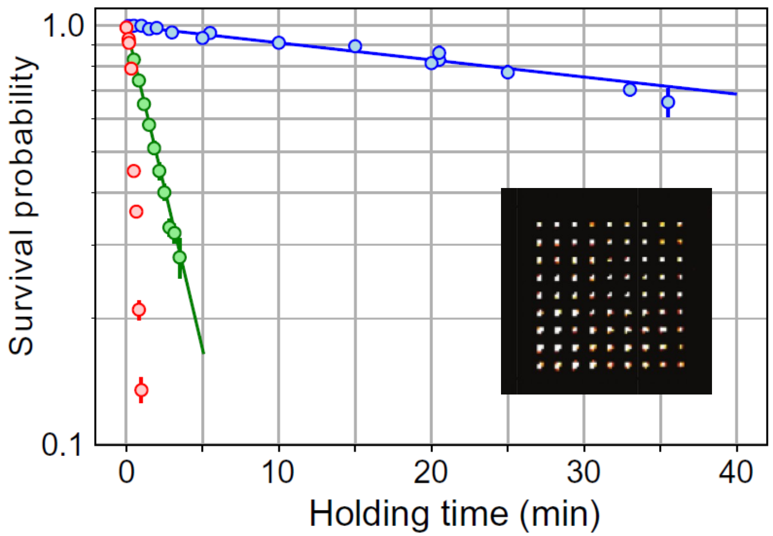
Towards more atoms: arrays in a cryostat

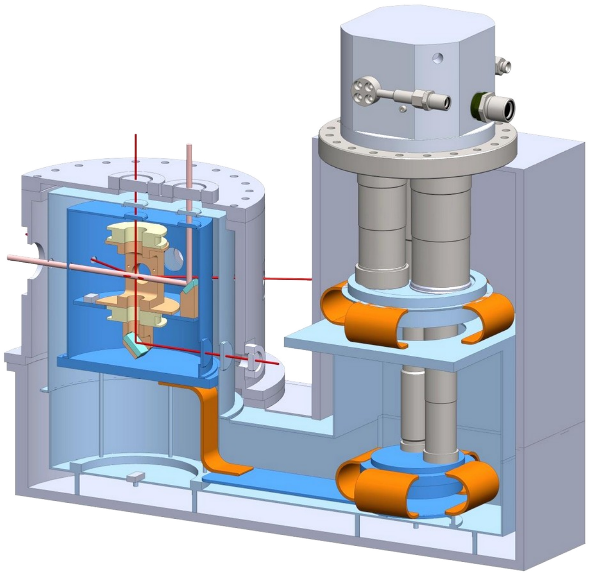




Trapping lifetime > 6000 s !

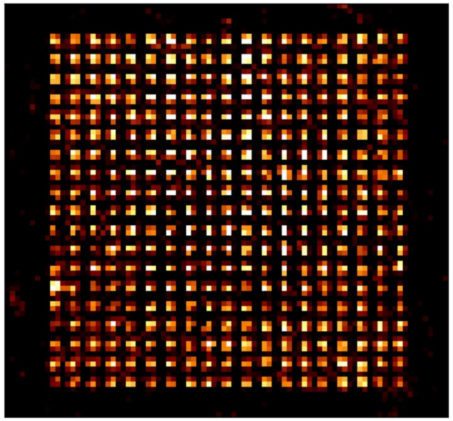
Towards more atoms: arrays in a cryostat



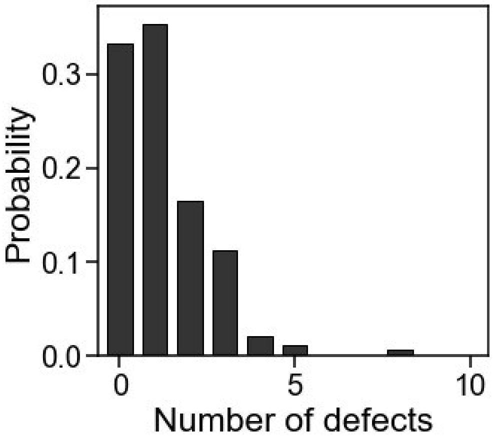


Trapping lifetime > 6000 s !

19 x 19



17 x 18



Now:

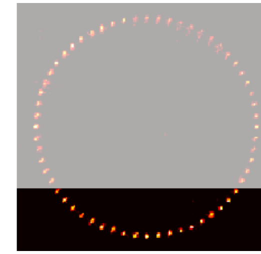
>300 atoms assembled
> 30% probability

Schymik *et al.*, PRA **106**, 022611 (2022)

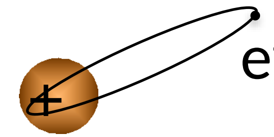
Questions?

Outline

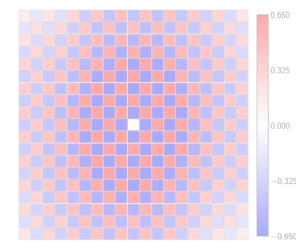
1. Arrays of individual atoms



2. **Rydberg atoms and their interactions**

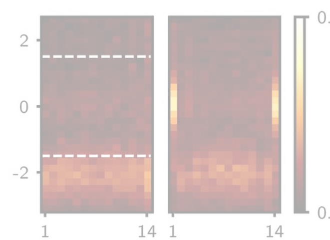


3. Examples of quantum simulations



A. Exploration of phase diagrams

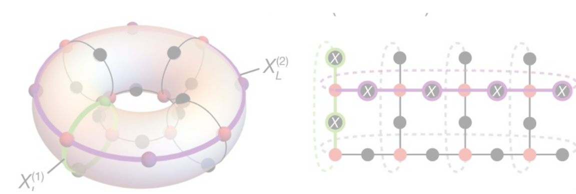
B. Out-of-Equilibrium dynamics



C. Ground state preparation & squeezing

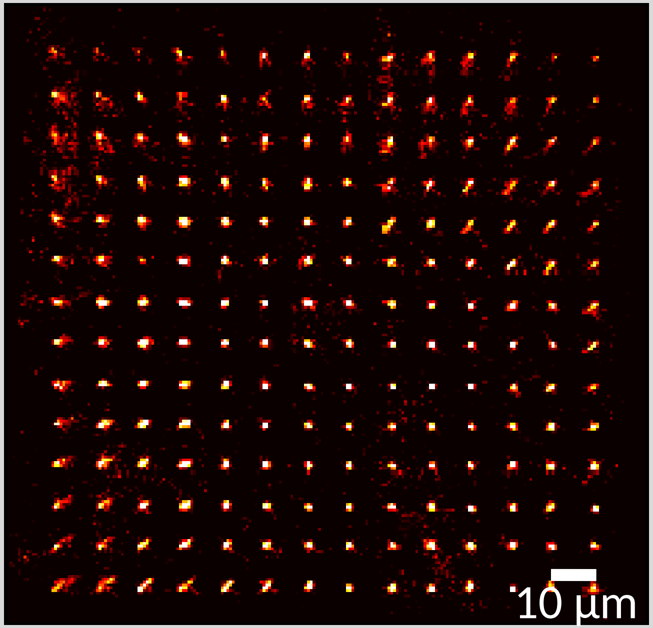
D. Synthetic Topological matter

4. Digital quantum computing



Arrays of interacting Rydberg atoms

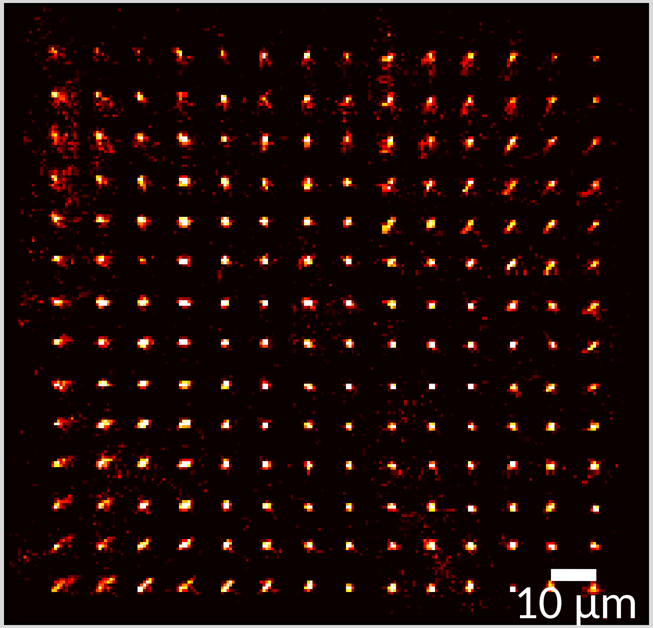
Arrays of atoms



Addressable

Arrays of interacting Rydberg atoms

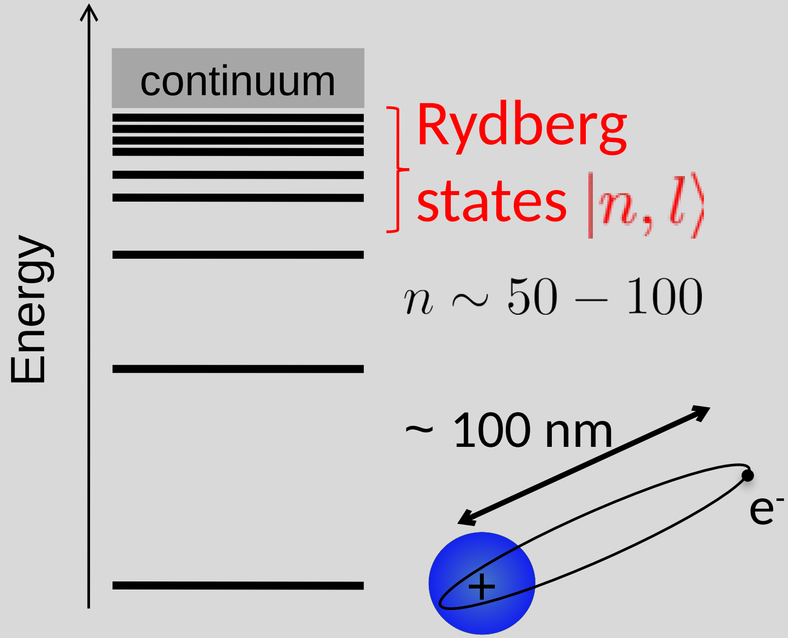
Arrays of atoms



Addressable

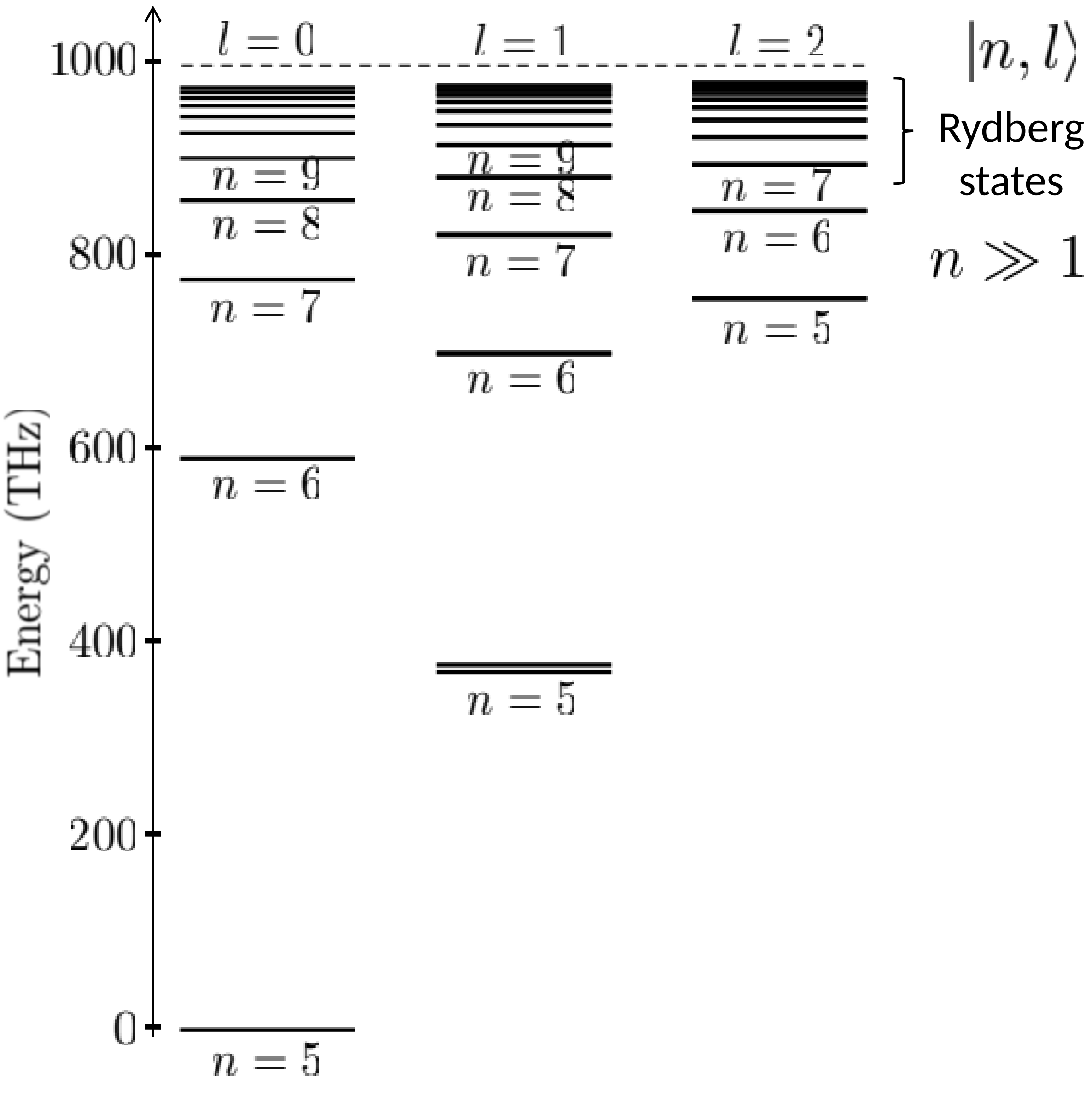
+

Rydberg atoms



Lukin, Zoller 2000
Saffman, RMP 2010
Browaeys, Nat. Phys. 2020

“Rydberg atom” = a highly excited atom (e.g. Rb)



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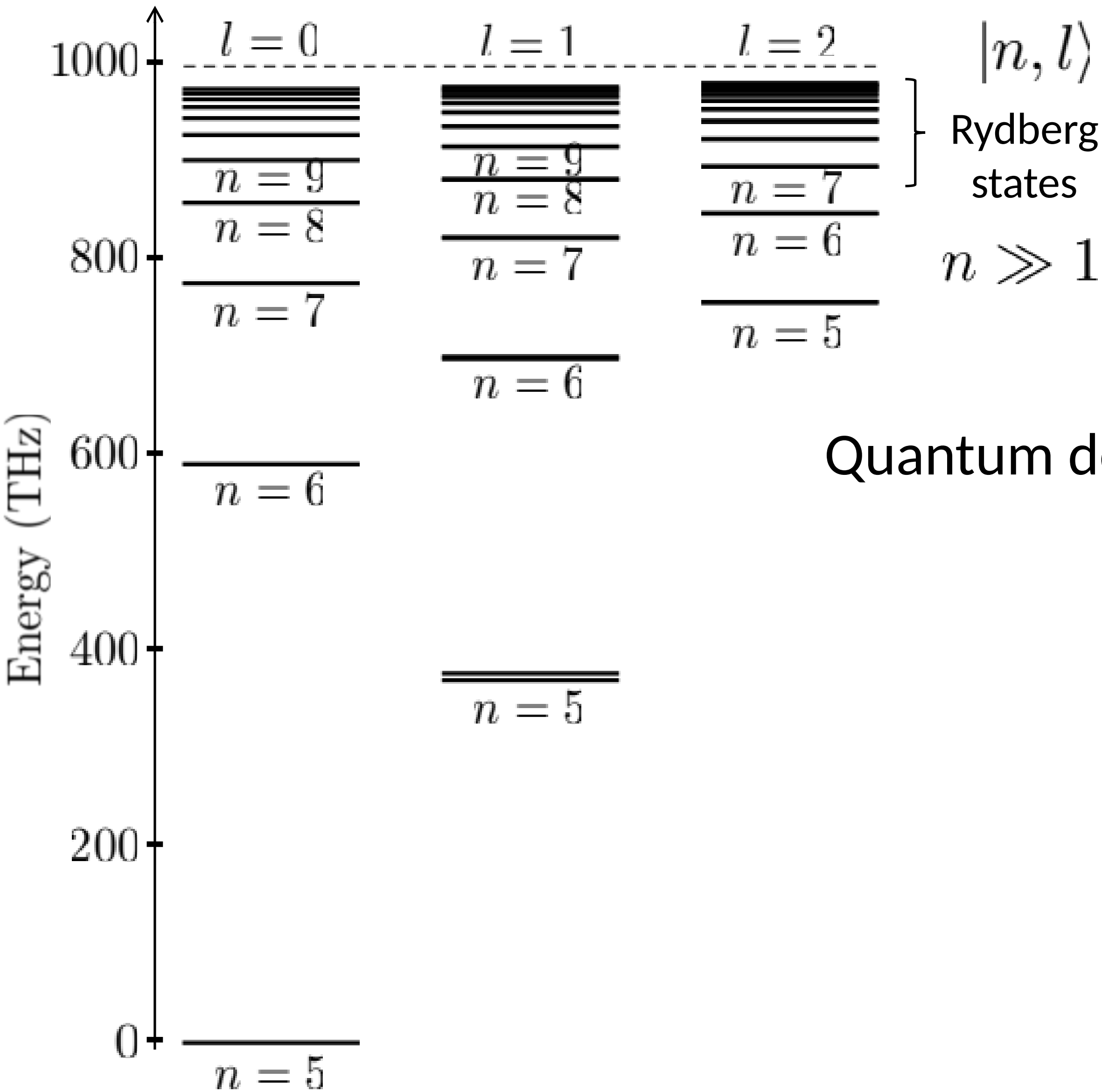
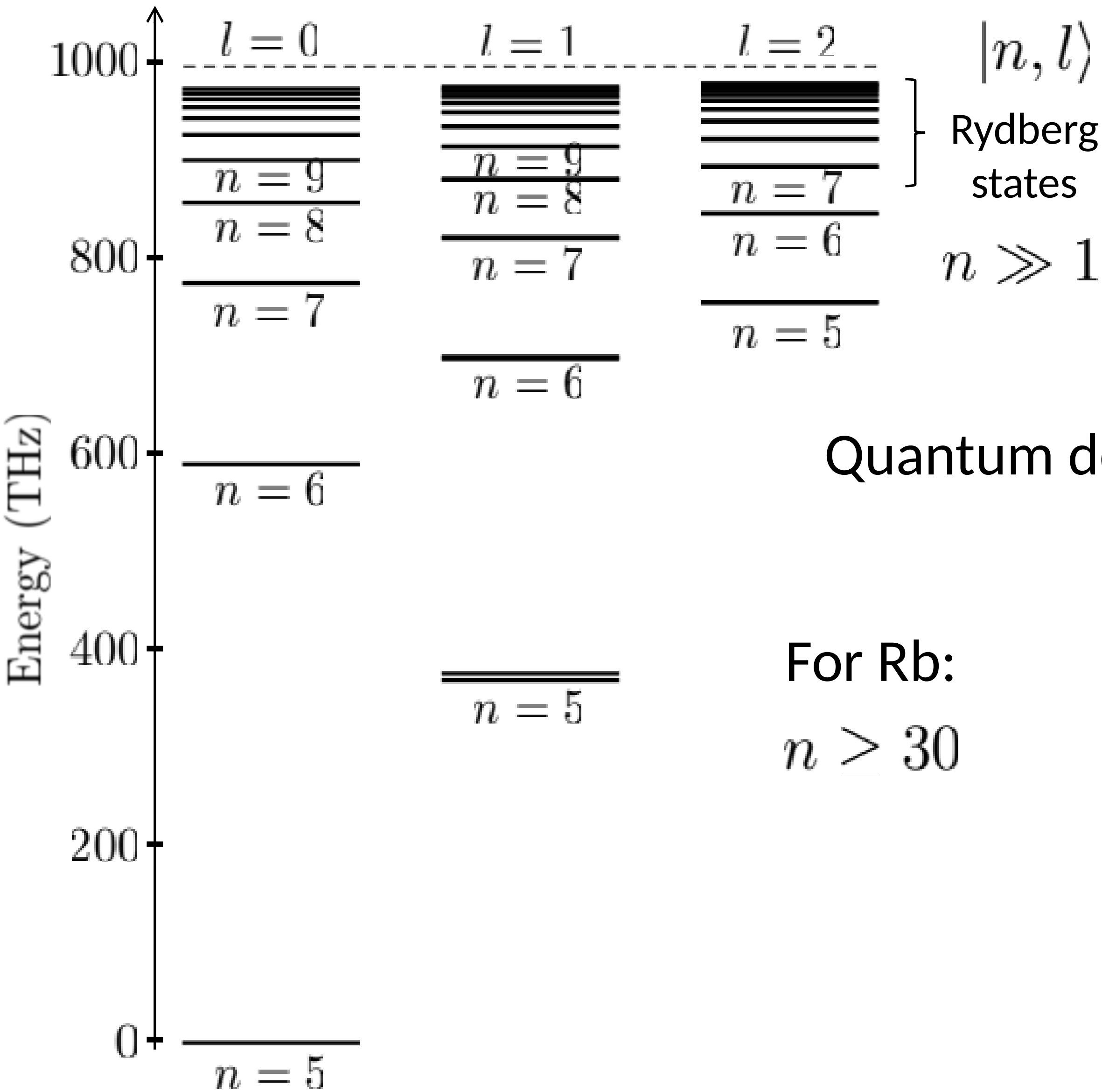


$$E_n = -\frac{R_y}{(n-\delta_{nlj})^2}$$

Quantum defects **(experimental)**

"Rydberg atom" = a highly excited atom (e.g. Rb)



$$E_n = -\frac{R_y}{(n - \delta_{nlj})^2}$$

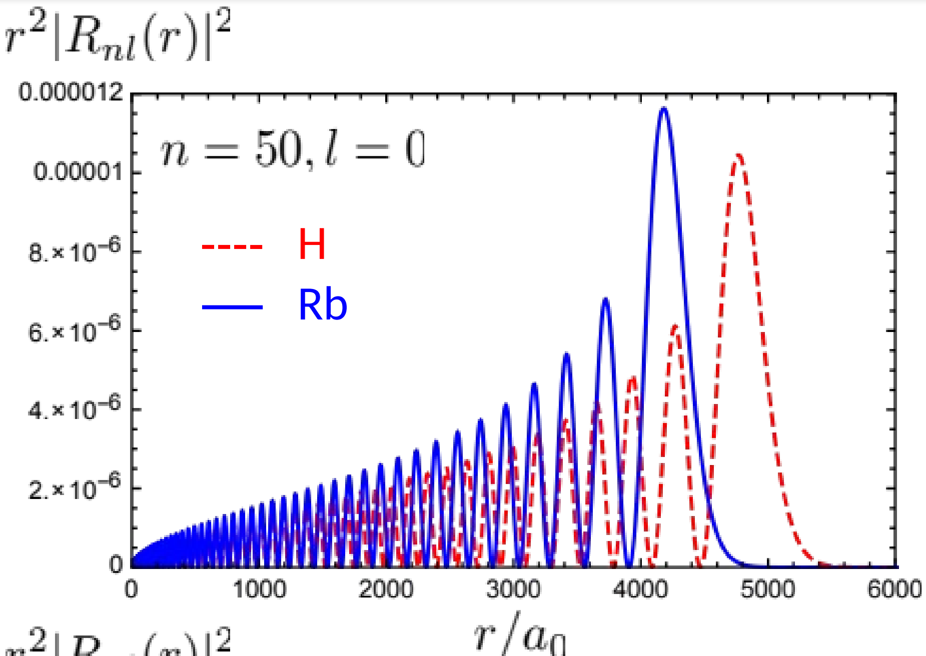
Quantum defects **(experimental)**

For Rb:

$n \geq 30$

L	J	$\delta_{L,J}$
0	1/2	3.131
1	1/2	2.654
	3/2	2.641
2	3/2	1.348
	5/2	1.346
3	5/2	0.016
	7/2	0.016

Radial wave-function for Rb

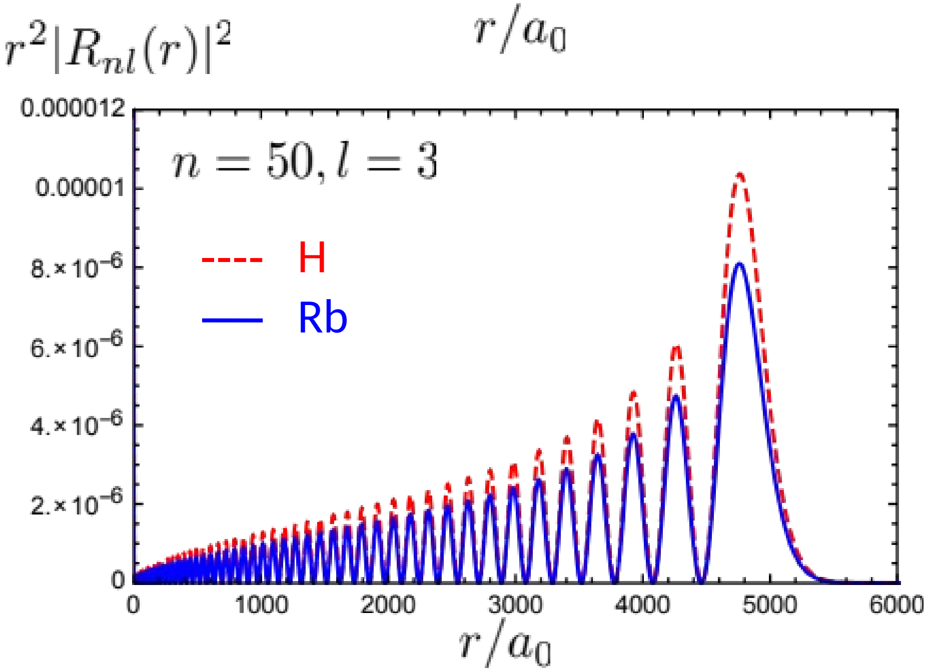


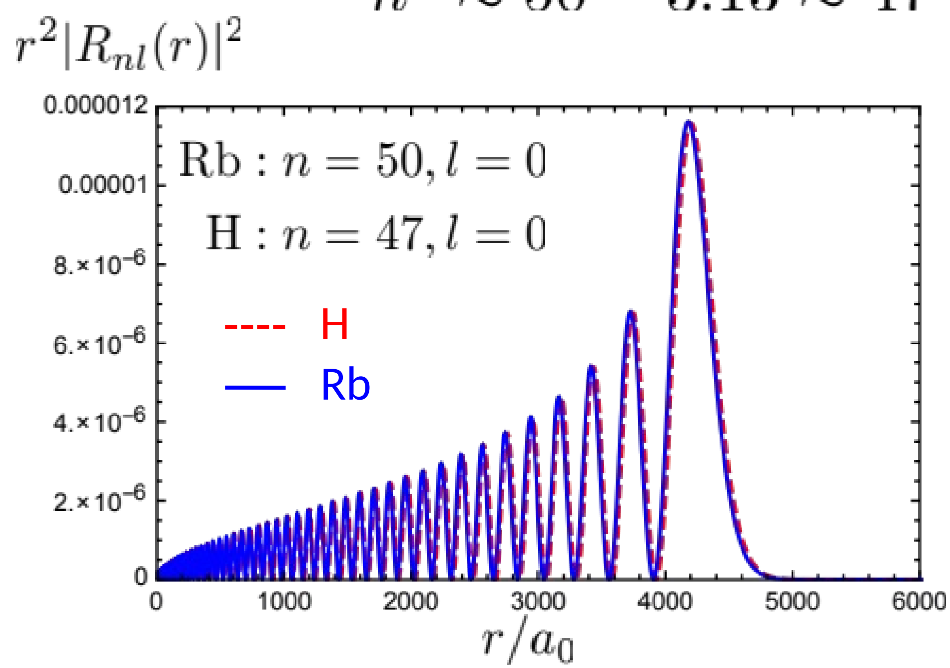
Numerov algorithm

Zimmerman, PRA 20, 2251 (1978)

$$n = 50 \Rightarrow n^* = n - \delta_0$$

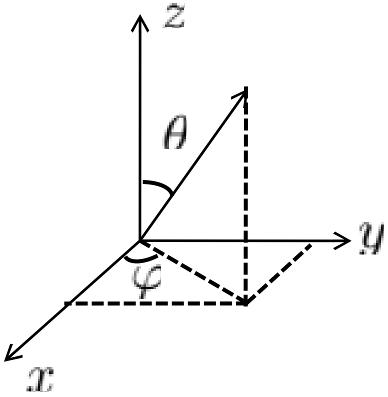
$$n^* \approx 50 - 3.13 \approx 47$$

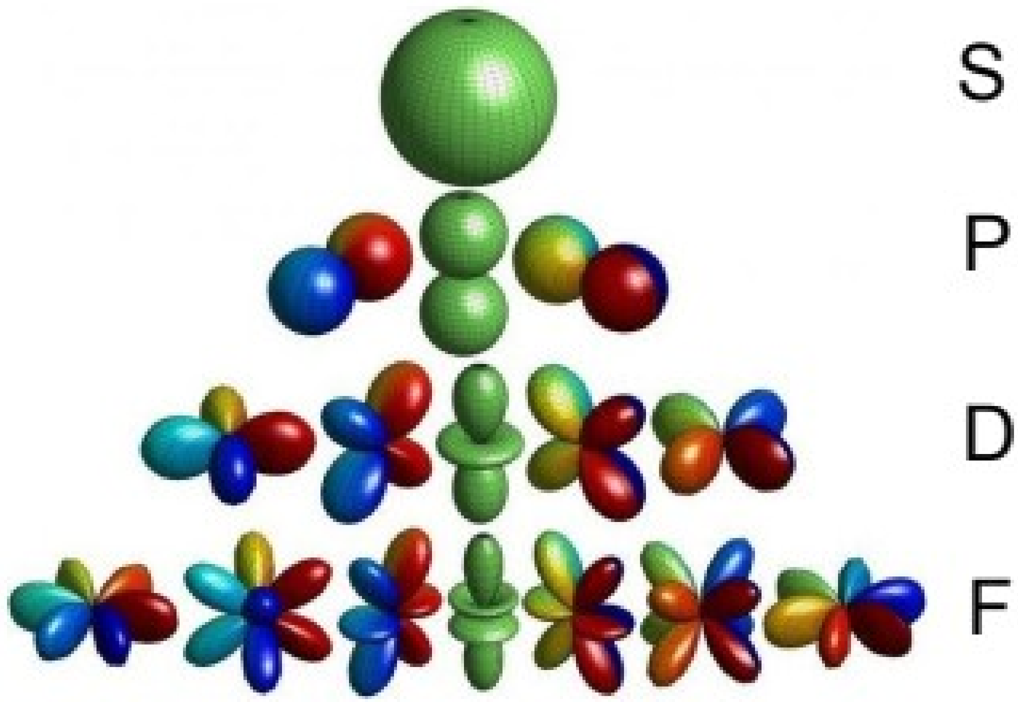




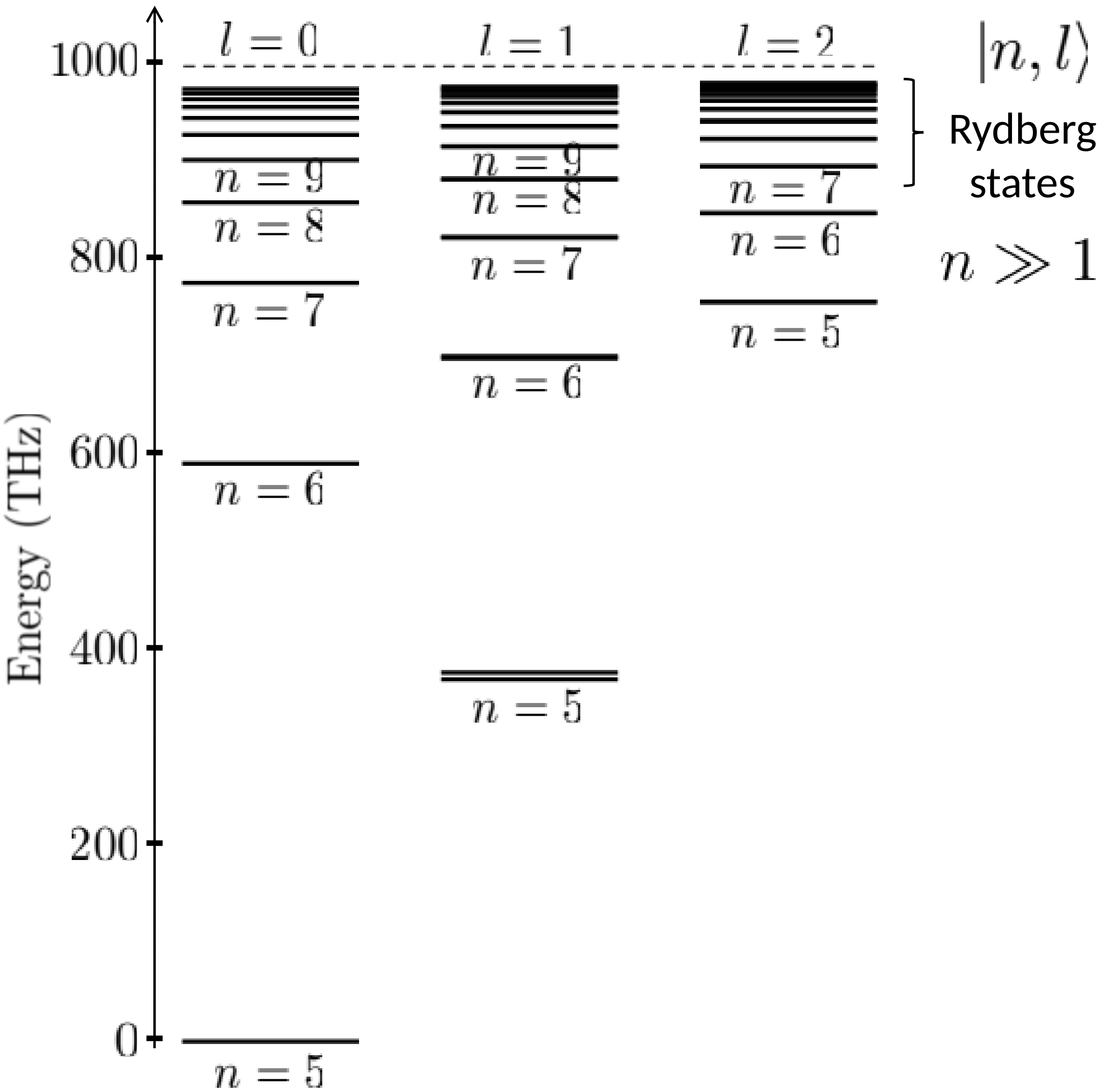
Angular wave-function

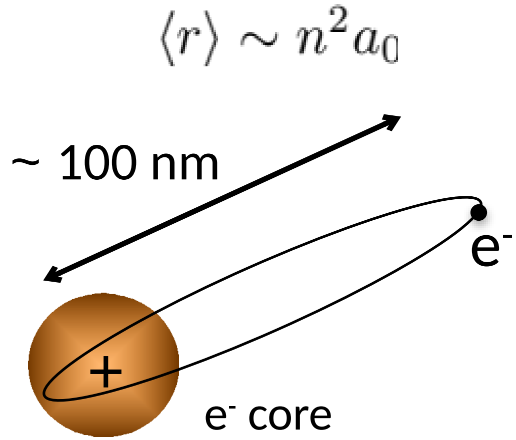
$$|Y_{lm}(\theta,\varphi)|^2$$



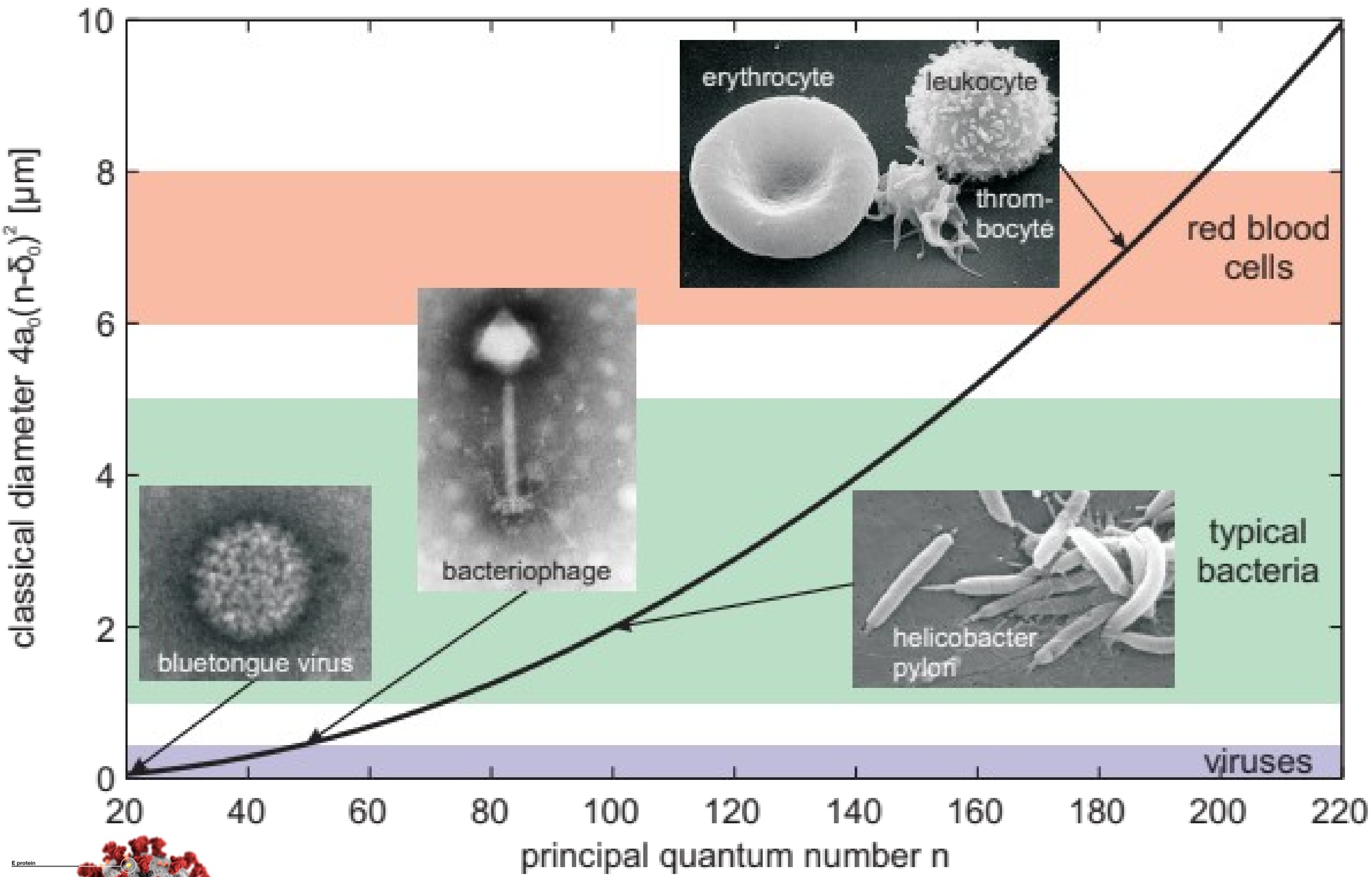


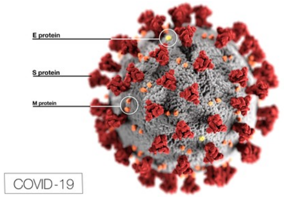
“Rydberg atom” = a highly excited atom (e.g. Rb)





Rydberg atoms are huge

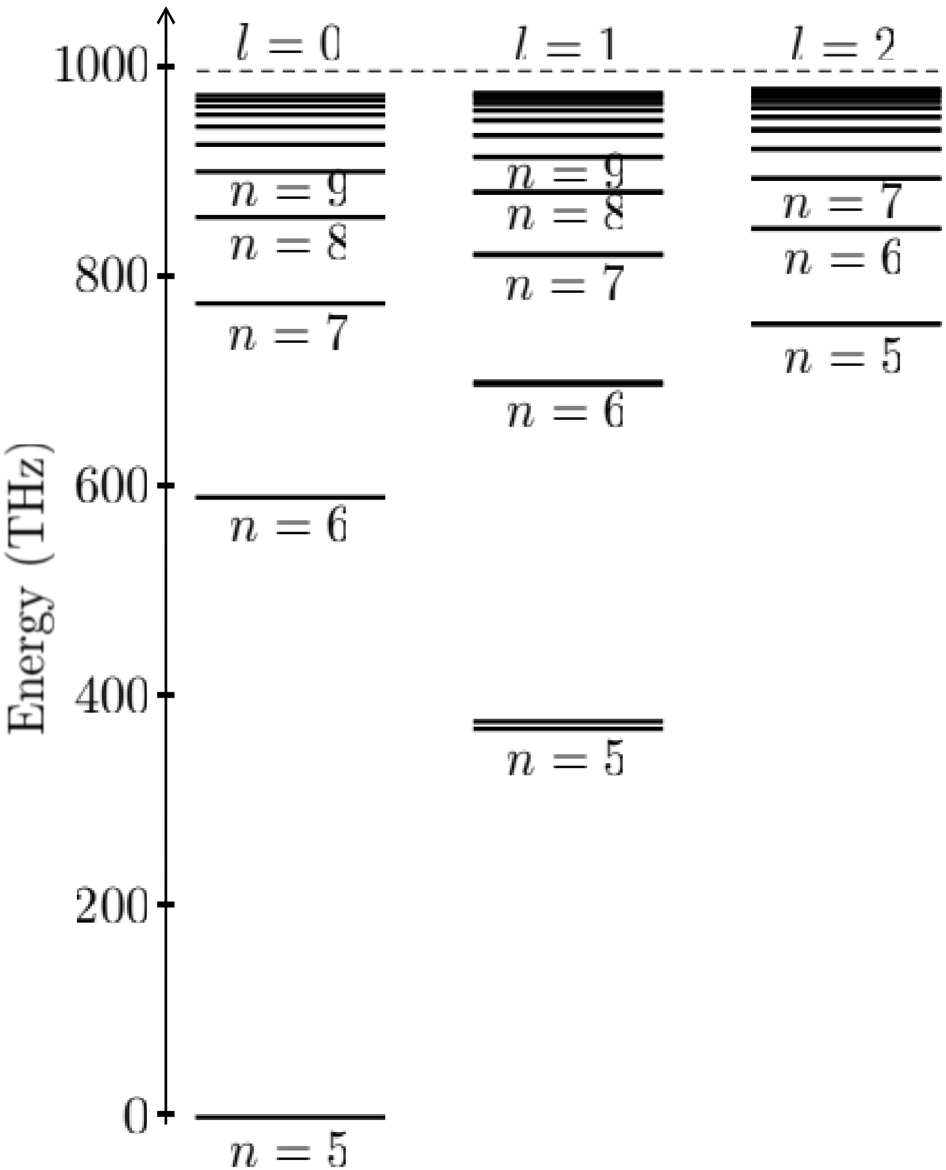




125 nm

J. Balewski, PhD thesis

“Rydberg atom” = a highly excited atom (e.g. Rb)

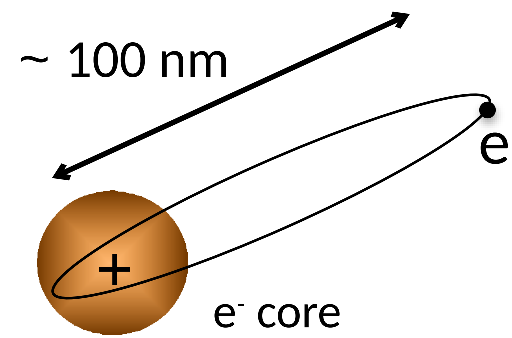


$|n, l\rangle$

Rydberg states

$n \gg 1$

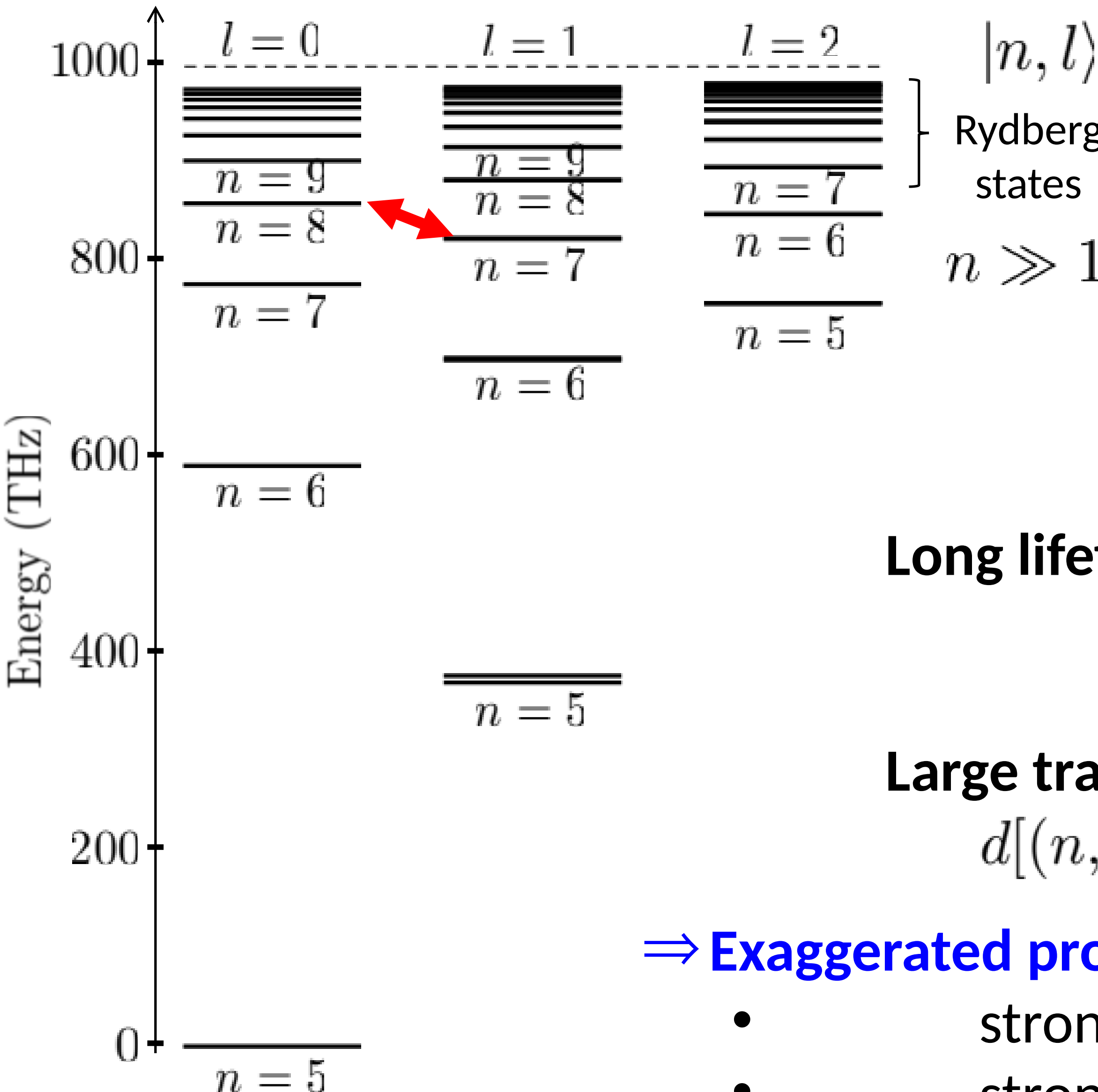
$\langle r \rangle \sim n^2 a_0$

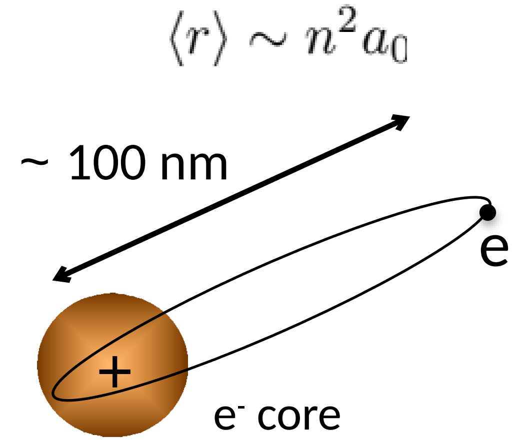


Long lifetime $\tau \sim n^3$

$n > 60$, $\tau > 100$ μs

"Rydberg atom" = a highly excited atom (e.g. Rb)





Long lifetime $\tau \sim n^3$

= *n* > 60, τ > 100 μs

Large transition dipole:

$$d[(n,l) \rightarrow (n, l \pm 1)] \sim n^2 e a_0$$

⇒ Exaggerated properties:

- strong interaction
- strong coupling to fields (DC, MW

Rydberg atoms have exaggerated properties

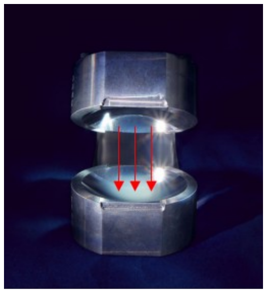
Table 1. Properties of Rydberg states.

Property	n−scaling	Value for $80S_{1/2}$ of Rb
Binding energy E_n	n^{-2}	-500 GHz
Level spacing $E_{n+1} - E_n$	n^{-3}	13 GHz
Size of wavefunction $\langle r \rangle$	n^2	500 nm
Lifetime τ	n^3	200 μs
Polarizability α	n^7	-1.8 GHz/(V/cm)^2
van der Waals coefficient C_6	n^{11}	4 THz $\cdot$ μm^6

Rydberg atoms: a few historical landmarks

1975 Spectroscopy using lasers (Gallagher, Kleppner, Haroche…)

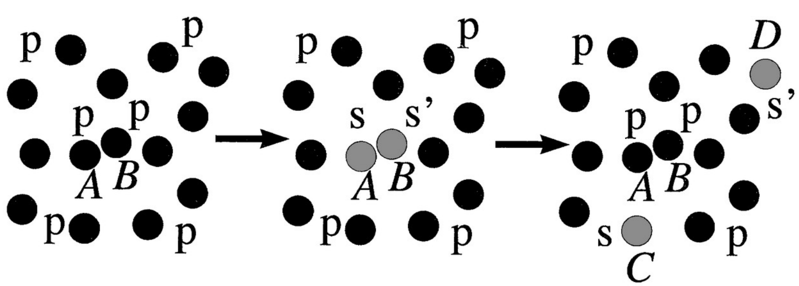
1980 – 2000 Cavity Quantum Electrodynamics using Rydbergs



High Q cavity: photon lifetime > 1ms
+ large dipole $\Rightarrow$
1 Rydberg interacts with 1 photon!

Haroche, Walther…

1998 Rydbergs meet cold atoms P. Pillet and T. Gallagher



p + p $\Rightarrow$ s + s'
p + s $\Rightarrow$ s + p
"Frozen" gas

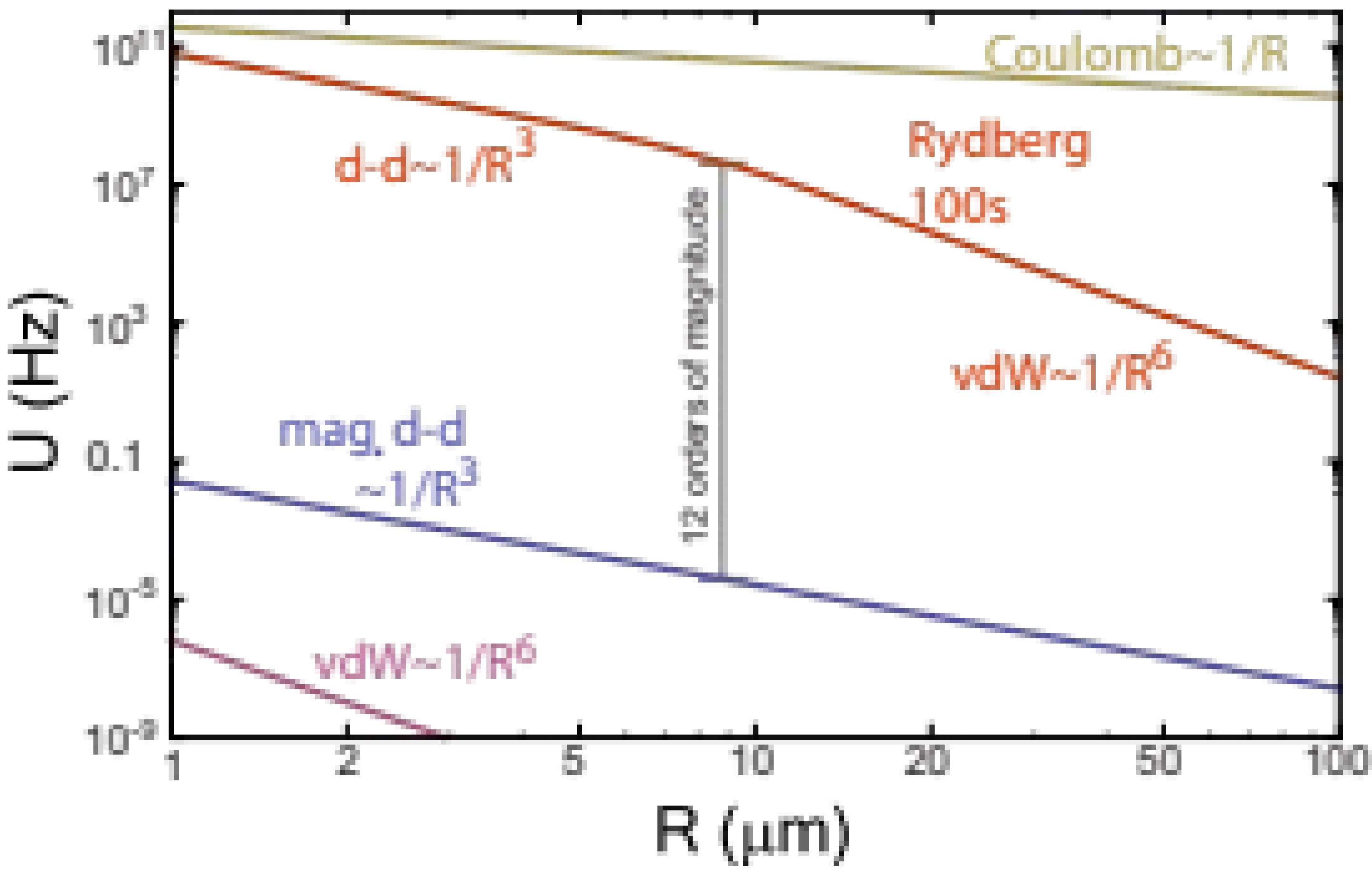
Anderson, PRL **80**, 249 (1998)
Mourachko, PRL **80**, 253 (1998)

Diffusion of excitation faster than motion $\Rightarrow$ correlations between all atoms

$k_B T$ << Interaction energy

$\Rightarrow$ T < 1 mK

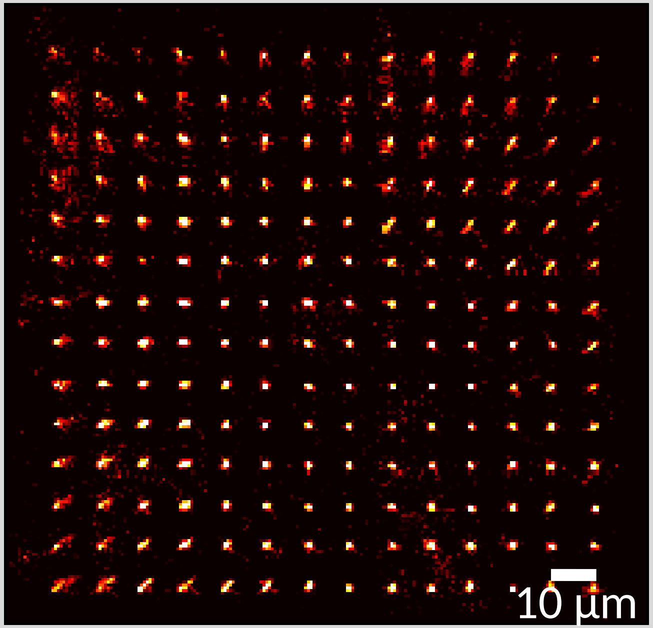
Strength of Rydberg interactions



"Quantum Information with Rydberg atoms", M. Saffman, T. Walker, K. Moelmer, Rev. Mod. Phys. **82**, 2313 (2010)

Arrays of interacting Rydberg atoms

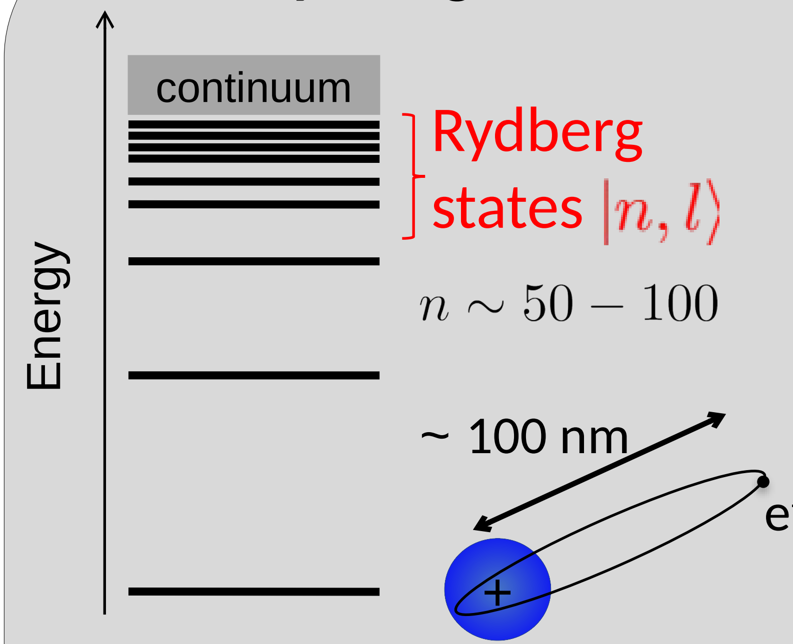
Arrays of atoms



Addressable

+

Rydberg atoms



Lifetime > 100 µs $\tau \sim n^3$

Transition dipole: $d \sim n^2$

Large dipole-dipole interactions

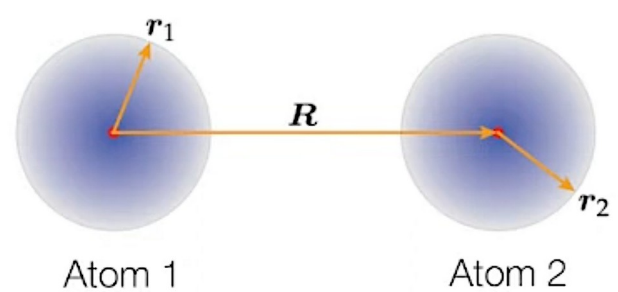
$R \approx 10\,\mu\text{m} \rightarrow V_{\text{int}}/h \approx 1 - 10\,\text{MHz}$

$T_{\text{int}} \approx \mu\text{s} \ll T_{\text{lifetime}}$

Lukin, Zoller 2000
Saffman, RMP 2010
Browaeys, Nat. Phys. 2020

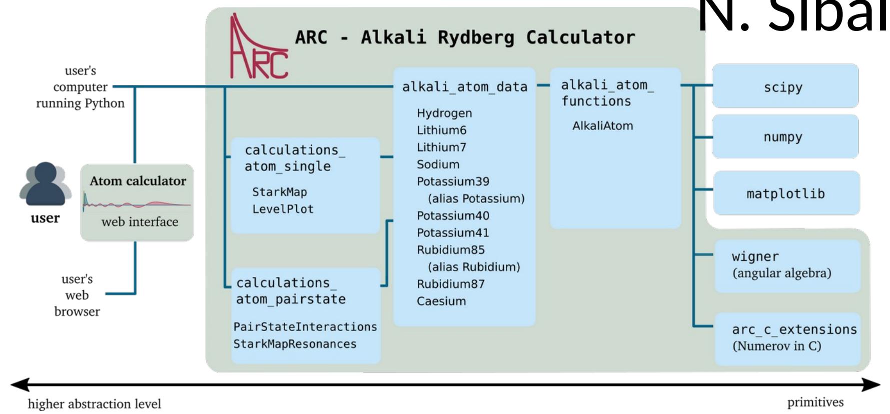
On-line interaction calculator for Rydberg atoms

Dipole-dipole interactions

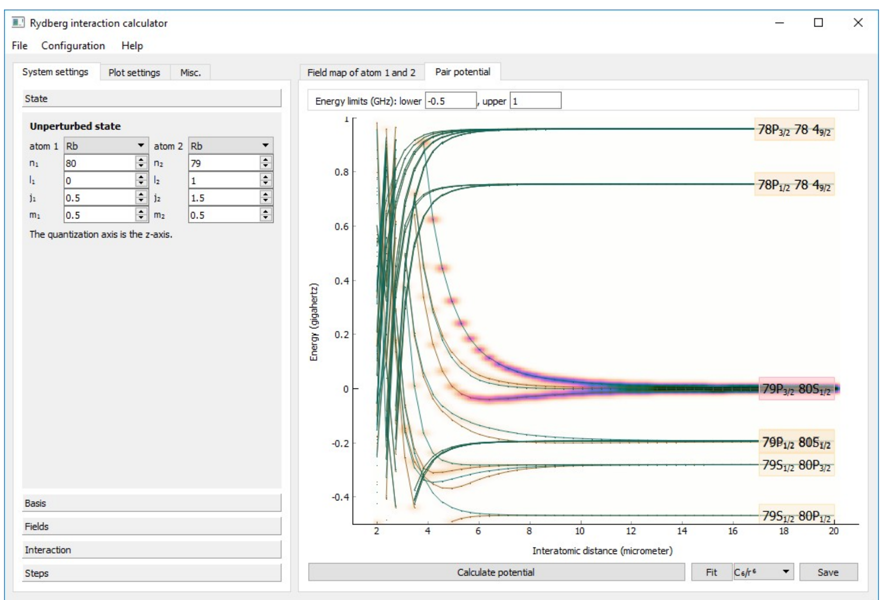


$$\hat{V} = \frac{e^2}{4\pi\epsilon_0}\left(\frac{1}{|\boldsymbol{R}|} + \frac{1}{|\boldsymbol{R} - \hat{\boldsymbol{r}}_1 + \hat{\boldsymbol{r}}_2|} - \frac{1}{|\boldsymbol{R} - \hat{\boldsymbol{r}}_1|} - \frac{1}{|\boldsymbol{R} + \hat{\boldsymbol{r}}_2|}\right)$$

N. Sibalic



https://arc-alkali-rydberg-calculator.readthedocs.io/



S. Weber

Docs » Pairinteraction - A Rydberg Interaction Calculator

Pairinteraction - A Rydberg Interaction Calculator

build passing | build passing | codecov 67% | pypi v0.9.5a0 | arXiv 1612.08053 | License GPLv3

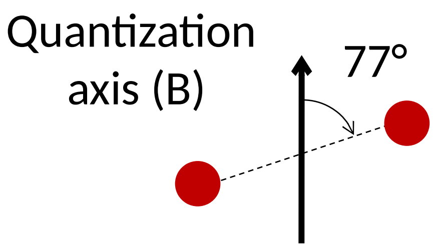
https://www.pairinteraction.org/

On-line interaction calculator for Rydberg atoms

https://pairinteraction.github.io/pairinteraction/sphinx/html/index.html

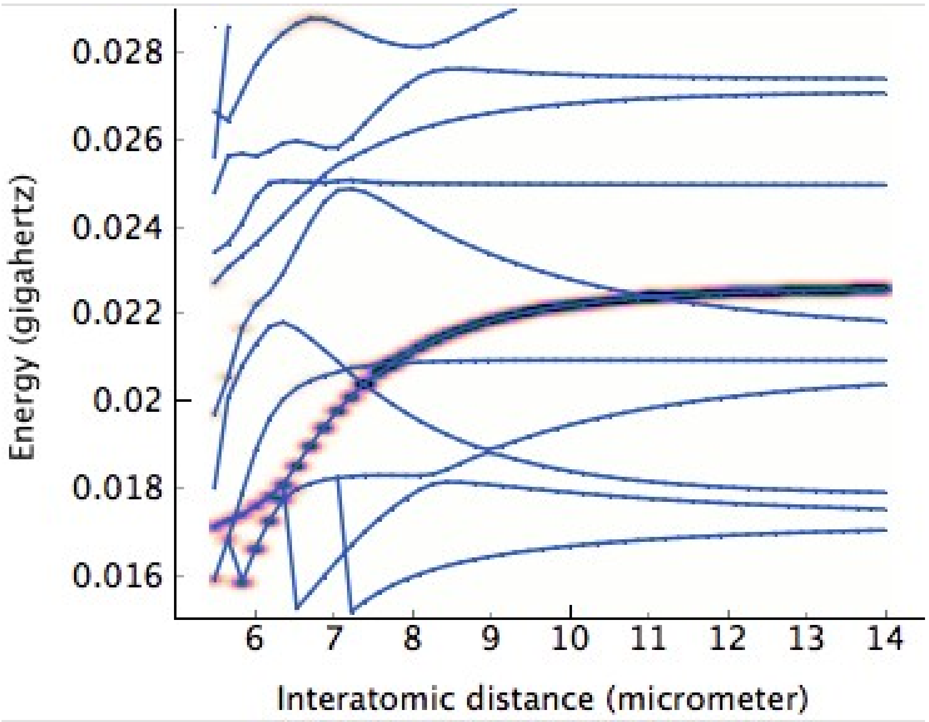
^{87}Rb

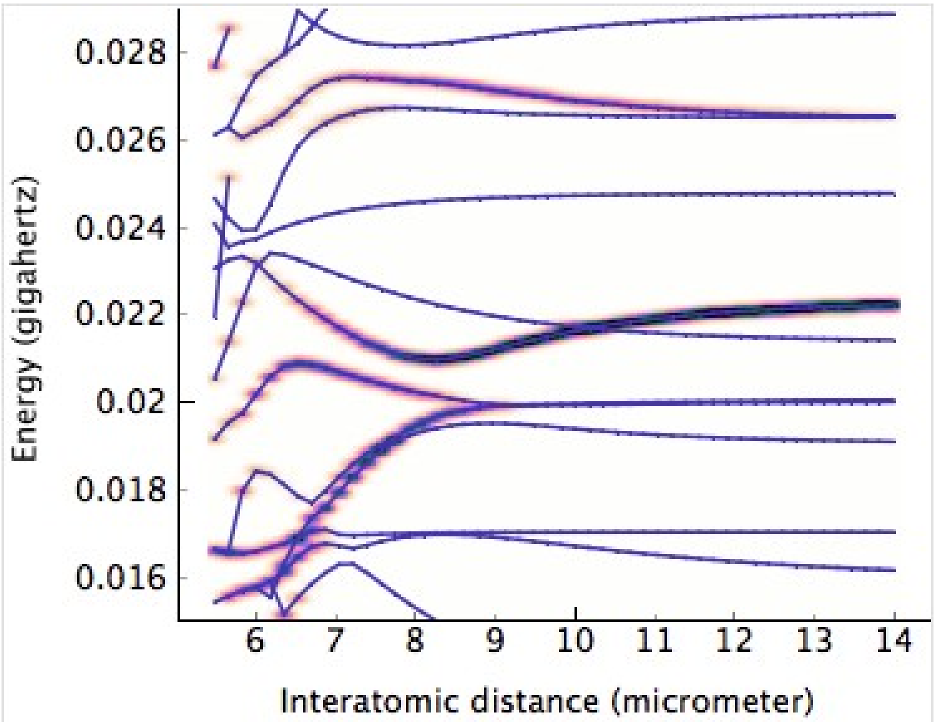
$61D_{3/2}$



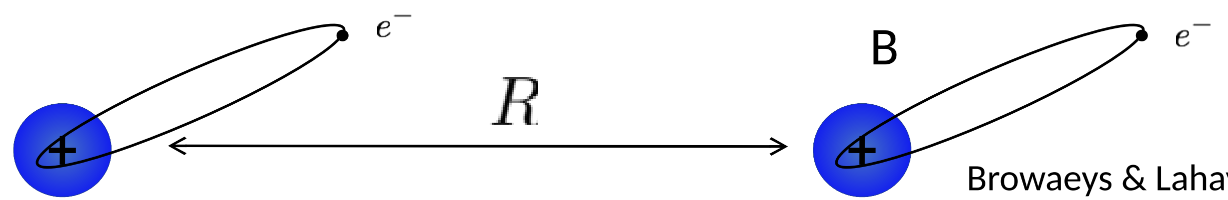
B = 6.9 G
E = 0 mV/cm

B = 6.9 G
E = 20 mV/cm

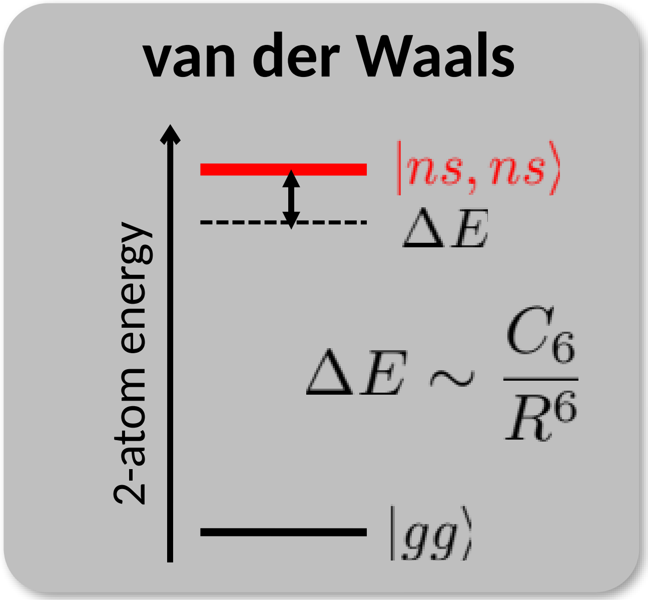


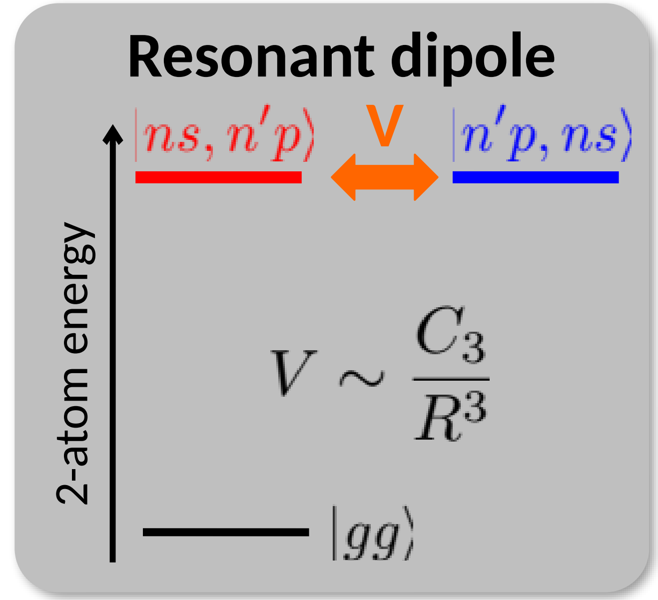


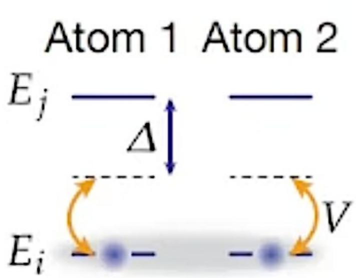
Interactions between Rydberg atoms and spin models



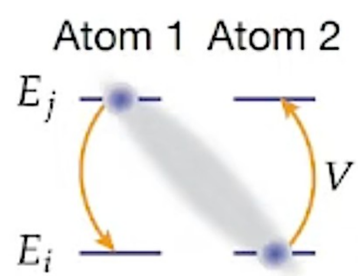
Browaeys & Lahaye, Nat.Phys. (2020)







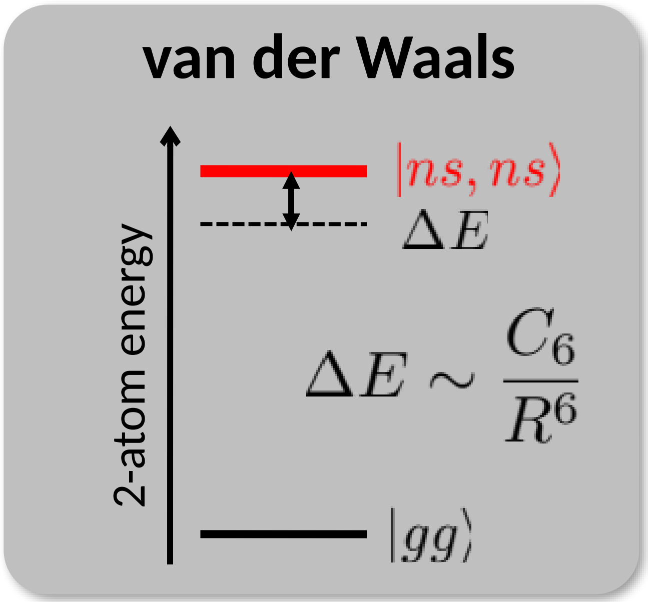
$$V(R) \sim \frac{|d_{sp}|^2 |d_{sp'}|^2}{(\Delta_1 - \Delta_2) R^6} \sim n^{11}$$

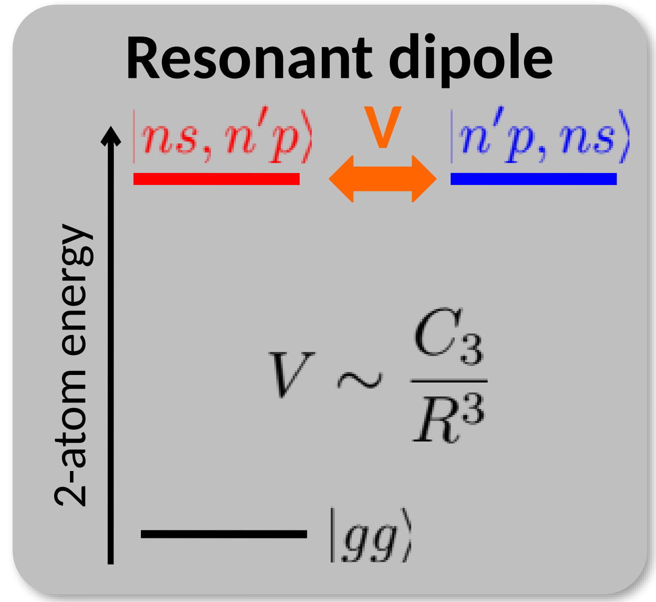


$$V(R) = \langle ns, n'p | V_{dd} | n'p, ns \rangle \sim \frac{d_{sp} d_{ps}}{R^3} \sim n^4$$

Interactions between Rydberg atoms and spin models

Browaeys & Lahaye, Nat.Phys. (2020)





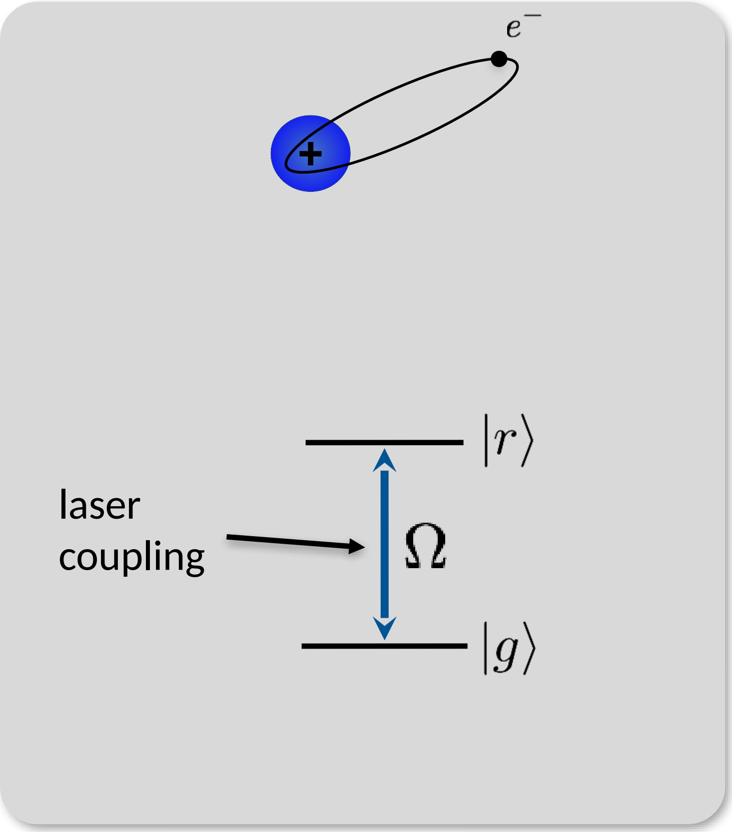
Quantum Ising

$$\hat{H} = \sum_{i \neq j} J_{ij} \hat{\sigma}_z^{(i)} \hat{\sigma}_z^{(j)}$$

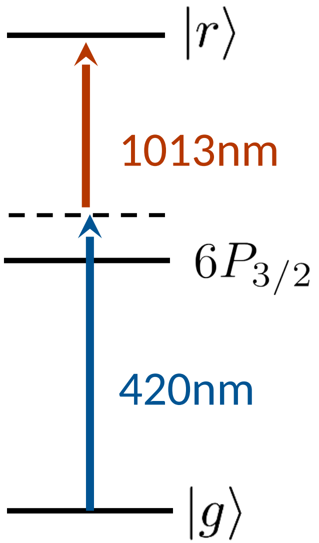
XY model

$$\hat{H} = \sum_{i \neq j} J_{ij} \left(\hat{\sigma}_i^+ \hat{\sigma}_j^- + \hat{\sigma}_i^- \hat{\sigma}_j^+ \right)$$

Coherent excitation to the Rydberg states



Bernien 2017, Levine 2019



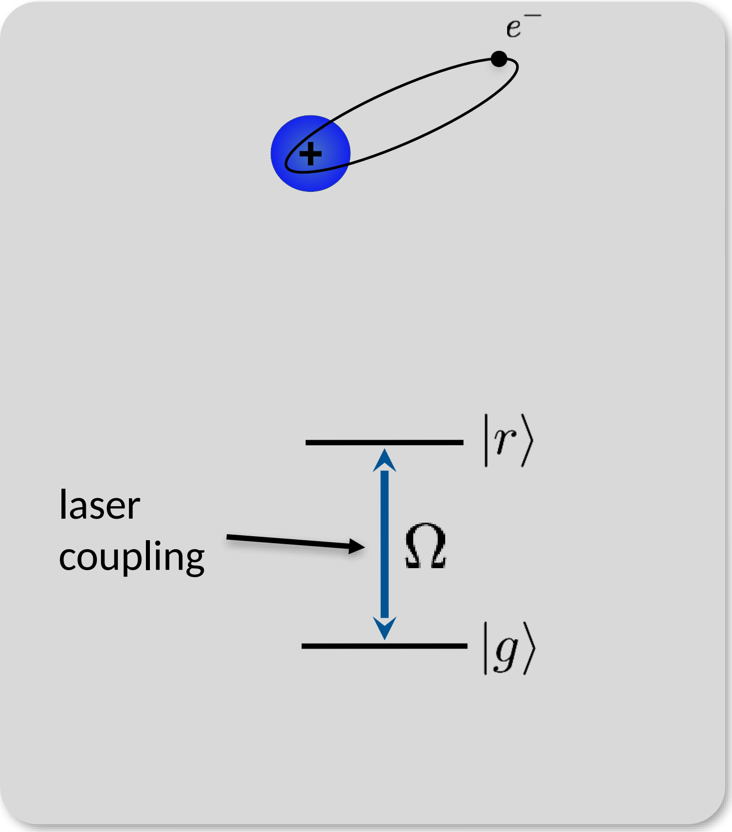
$\tau_{6P_{3/2}} = 113\,\mathrm{ns}$

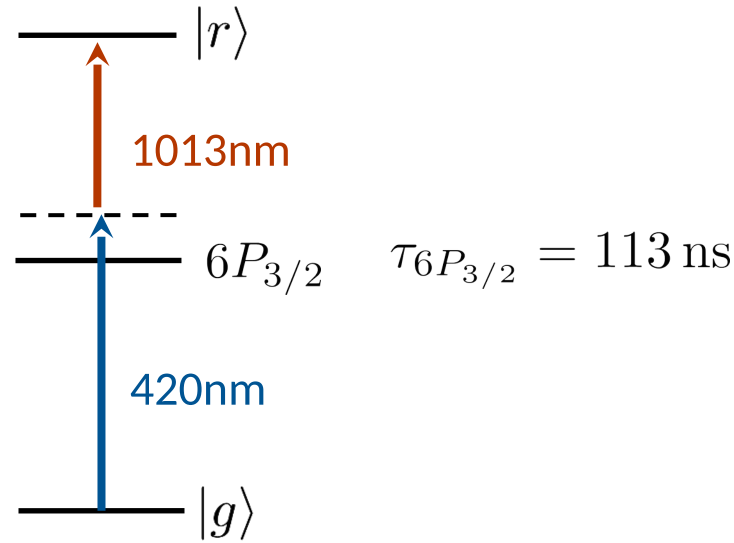
Effective Rabi frequency: $\Omega = \frac{\Omega_\mathrm{R}\Omega_\mathrm{B}}{2\Delta}$

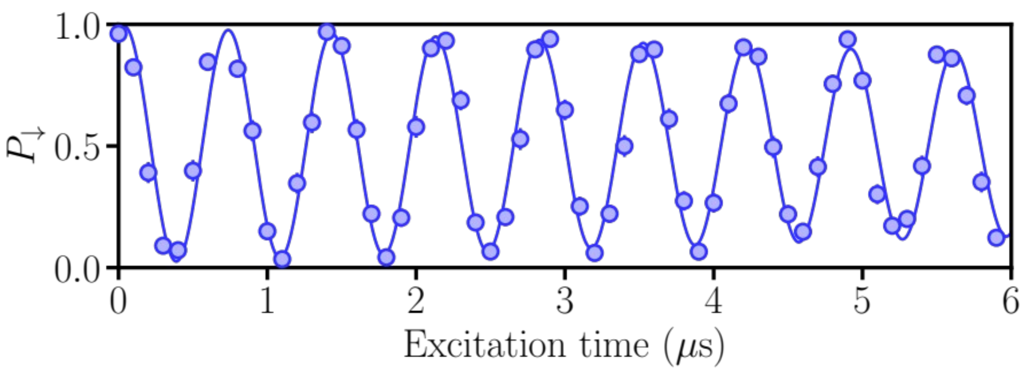
Light-shift: $\delta_\mathrm{eff} = \delta - \left(\frac{|\Omega_B|^2}{4\Delta} - \frac{|\Omega_R|^2}{4\Delta}\right)$

Coherent excitation to the Rydberg states

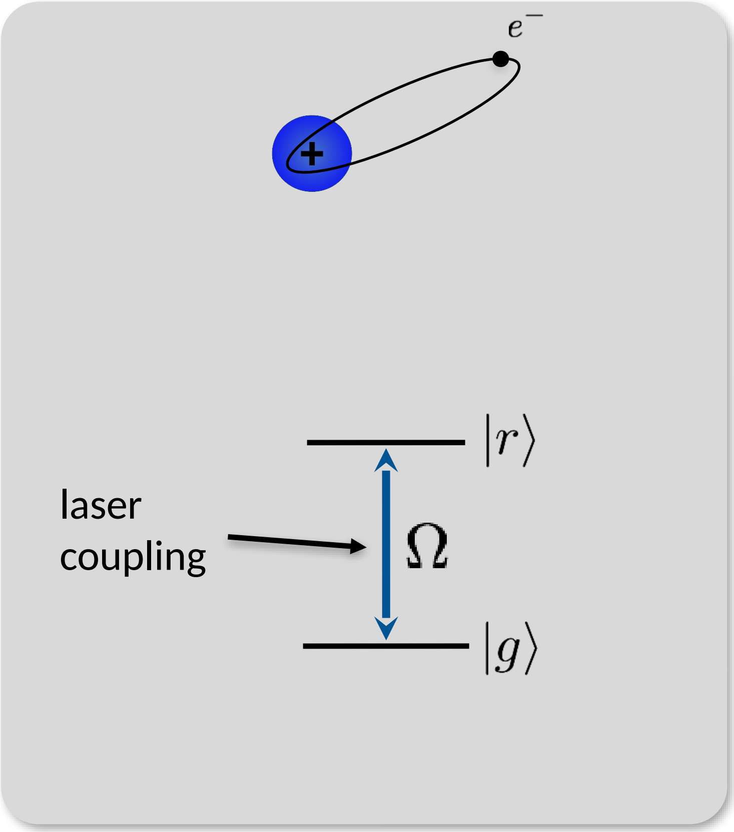
Bernien 2017, Levine 2019



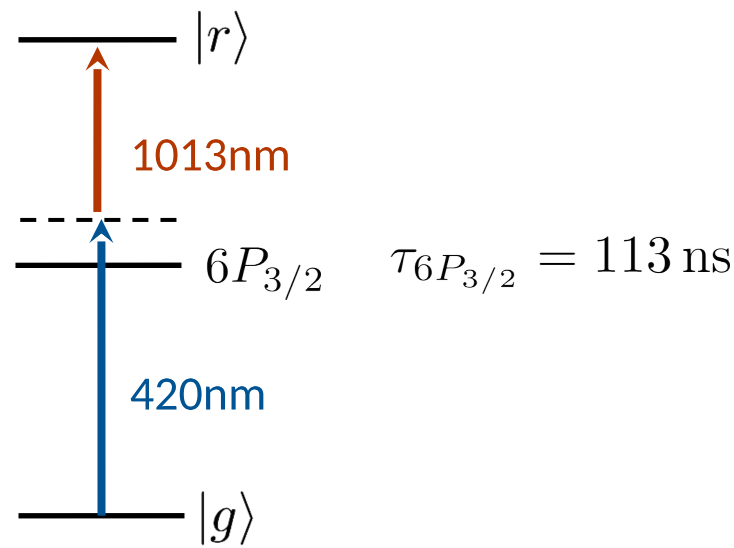




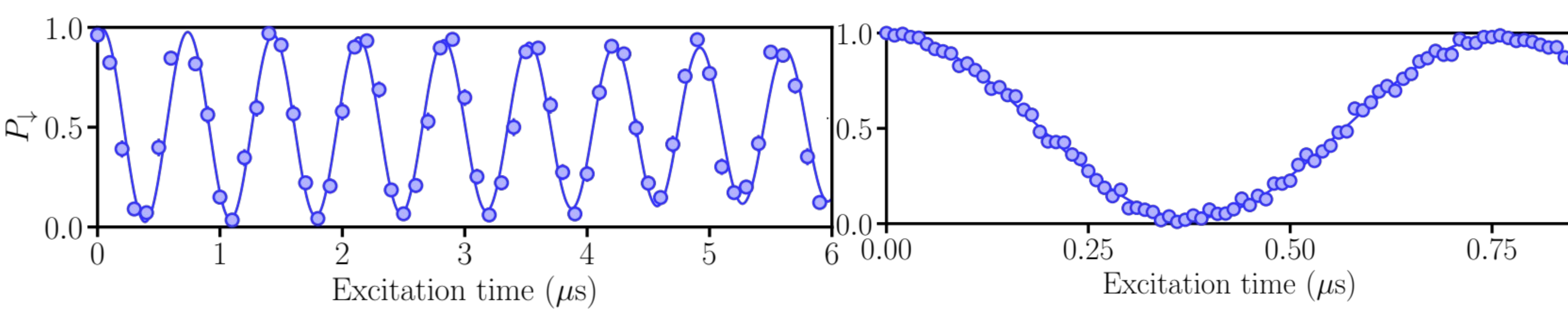
Coherent excitation to the Rydberg states



Bernien 2017, Levine 2019

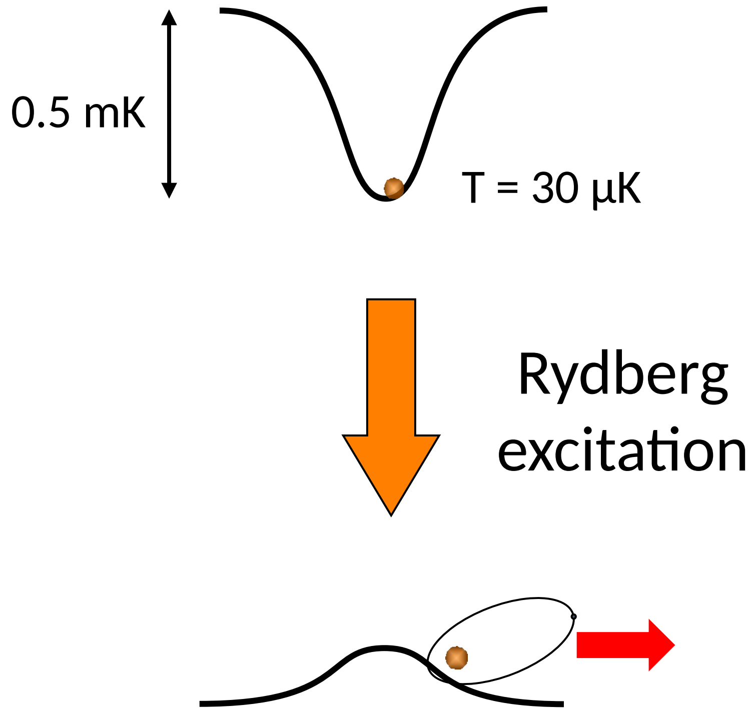


Rydberg excitation probability (-pulse):
raw data 97%, corrected 99%



Optical detection of Rydberg atoms

Atom loss

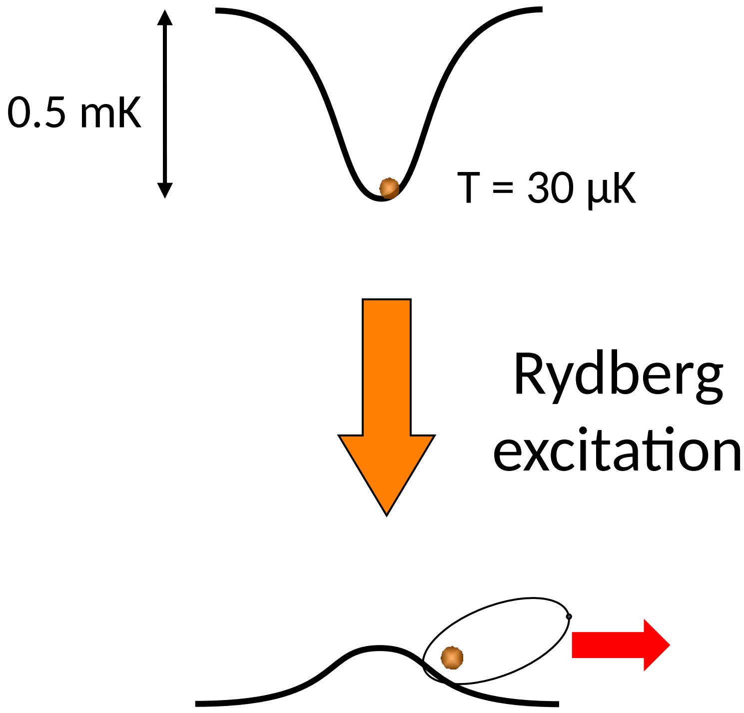


Leave trapping region
(1 μm) in < 5 μsec

Efficiency > 95%

Optical detection of Rydberg atoms

Atom loss



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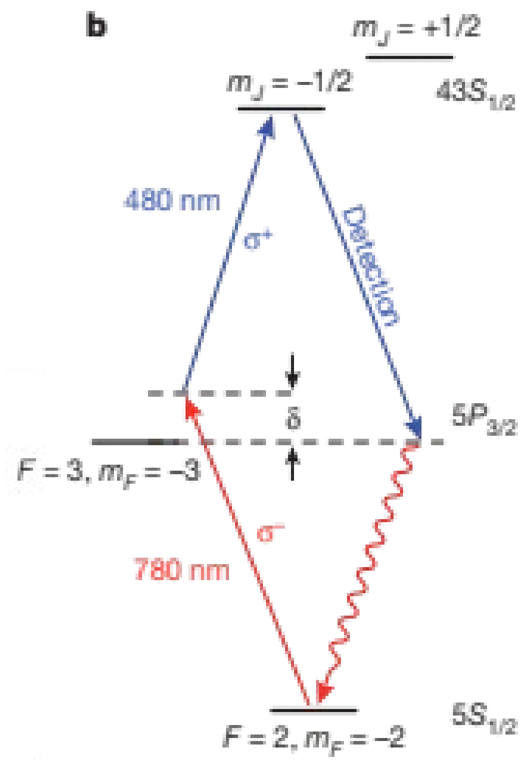
"Optical" detection

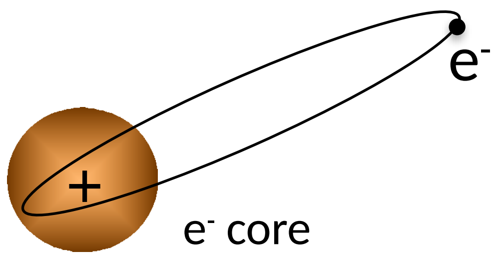


Schauss, Nature **491**, 87 (2012)

Efficiency > 95%

Trapping Rydberg atoms

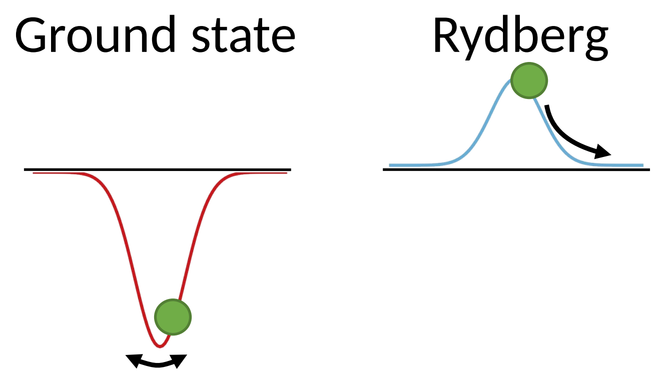
Ponderomotive potential



Rydberg = ~ almost free e⁻

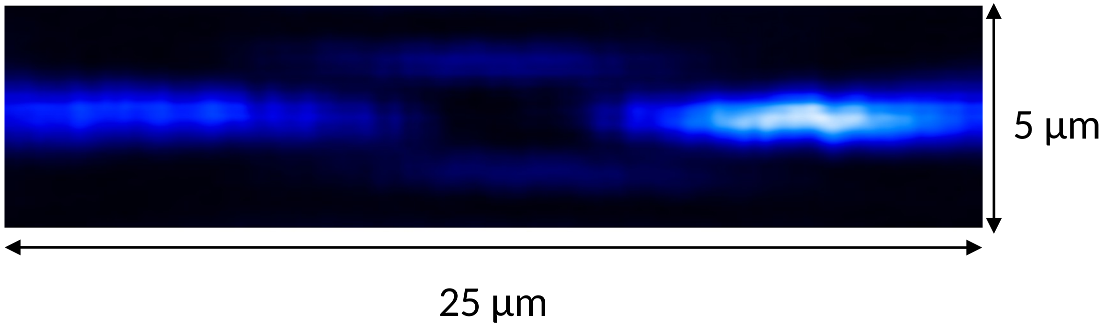
E-field at $\omega \Rightarrow V_{\mathrm{P}} = \frac{q^2}{4m\epsilon_0\omega^2}E^2$

Rydberg not trapped in tweezers



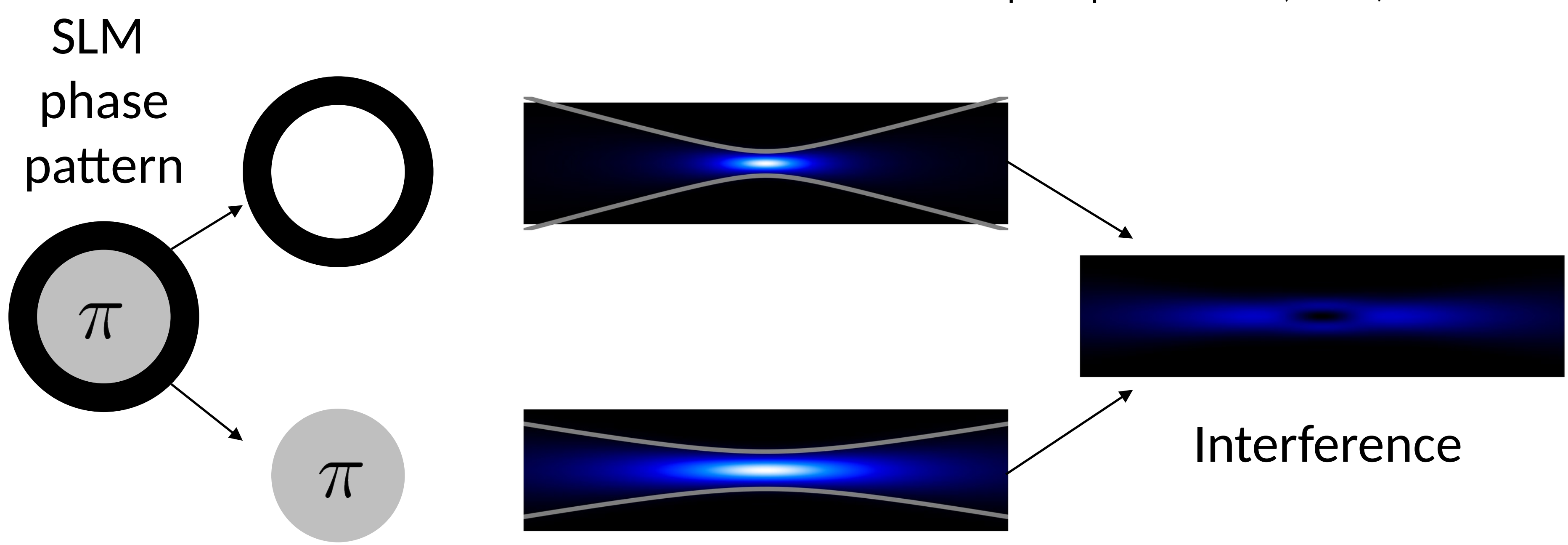
Solution: "hollow trap" for Rydberg trapping

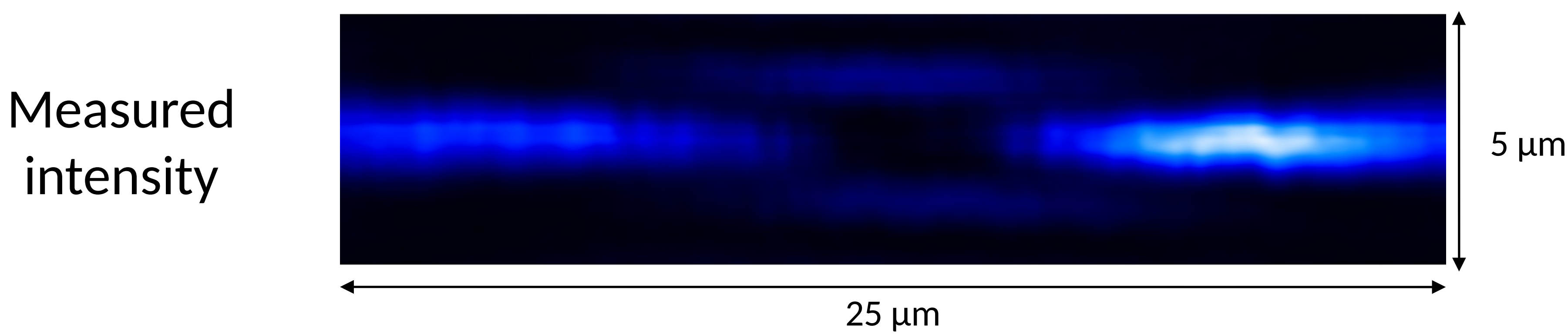
Holographic generation of bottle-beam trap (measured intensity)



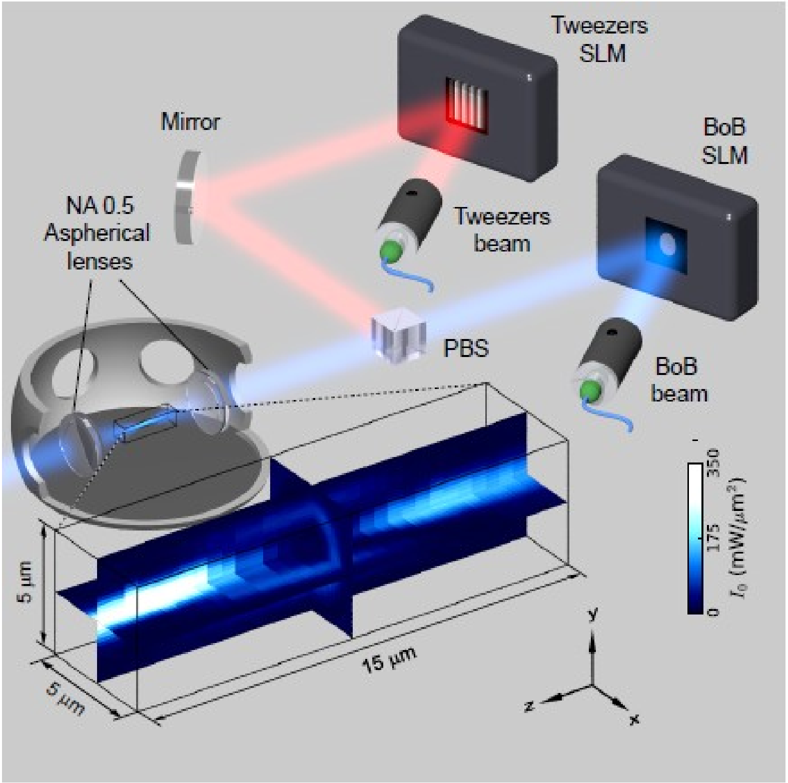
The bottle beam trap

Chaloupka Opt. Lett. 1997; Ozeri, PRA 1999





Demonstration of Rydberg trapping



Barredo, PRL **124**, 023201 (2020)

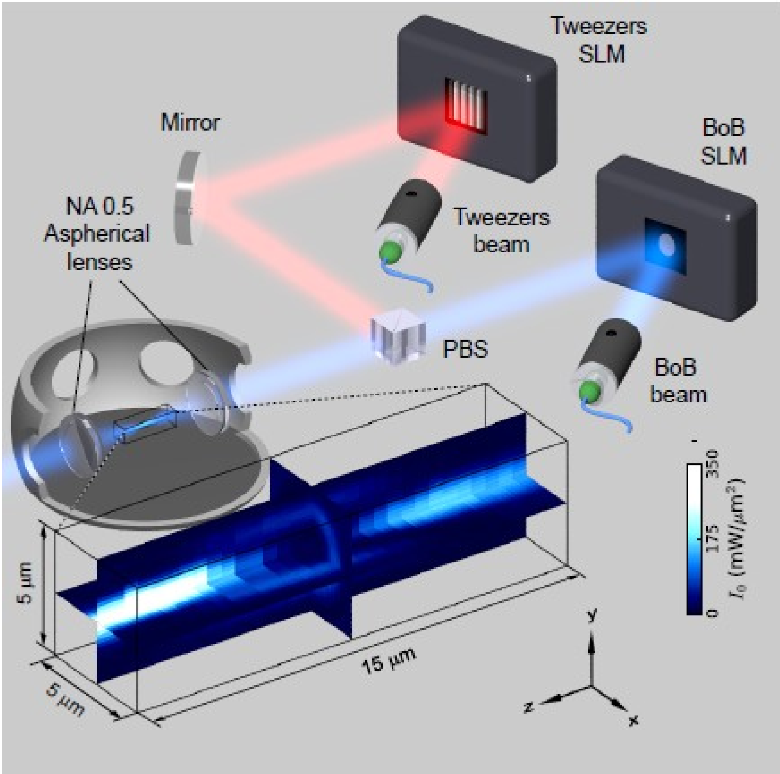
Ponderomotive 'Bottle beam' trap

$$U_{nljm_j}(\boldsymbol{R}) = \int d^3r\, V_P(\boldsymbol{R}+\boldsymbol{r})\, |\psi_{nljm_j}(\boldsymbol{r})|^2$$

Ponderomotive potential for the electron (repulsive)

$$V_P(\boldsymbol{r}) = \frac{q_e^2 I(\boldsymbol{r})}{2 m_e \varepsilon_0 c\, \omega_L^2}$$

Demonstration of Rydberg trapping



Barredo, PRL **124**, 023201 (2020)

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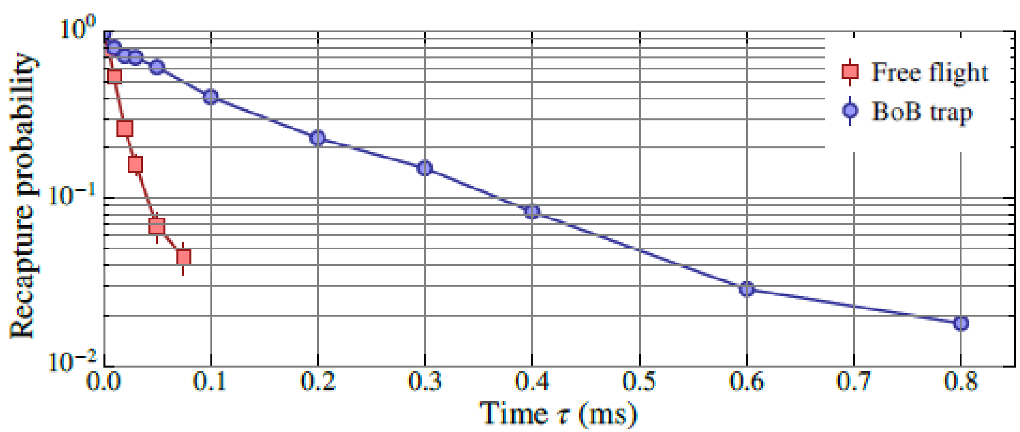
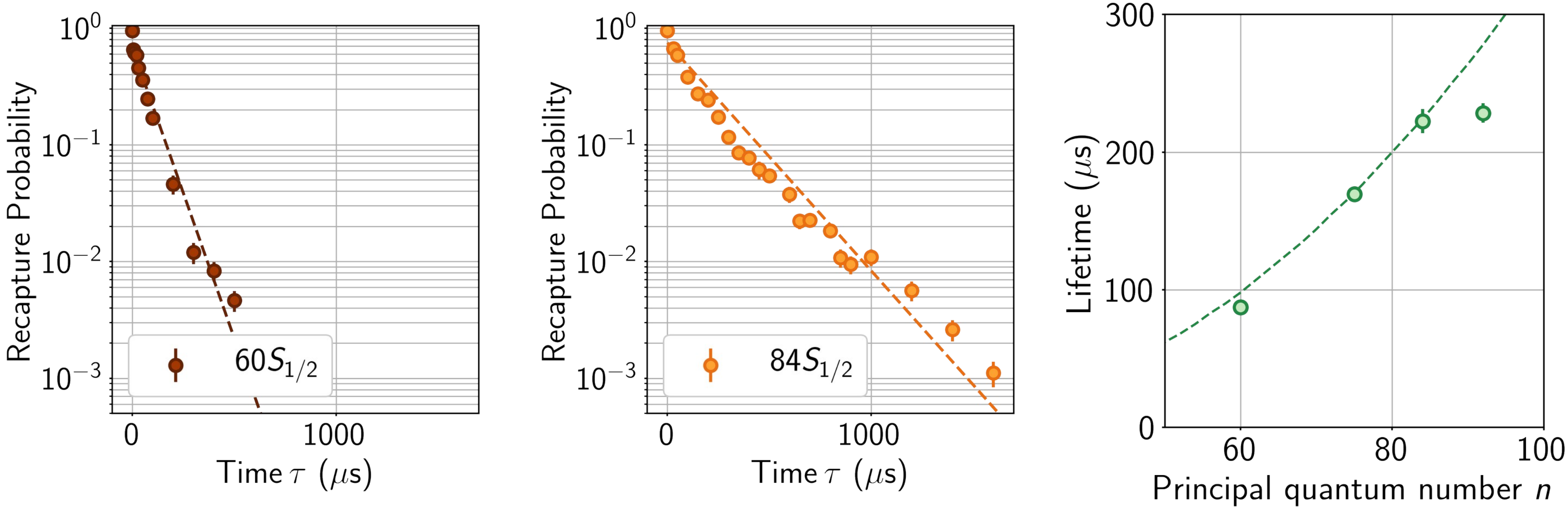


Also:
circular atoms
Brune & Sayrin
PRL 2020

Measuring Rydberg lifetimes

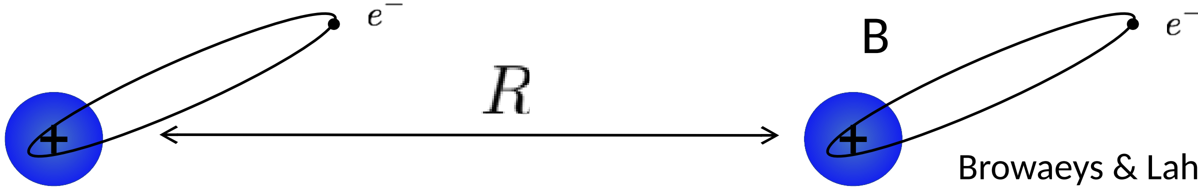


- ✓ Microwave manipulation of the Rydberg state
- ✓ Exchange dynamics between two trapped Rydberg atoms

Barredo, PRL **124**, 023201 (2020)

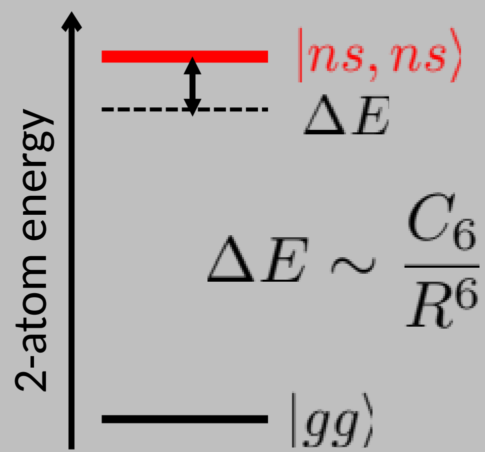
See also Cortiñas, PRL 124, 123201 (2020)

Interactions between Rydberg atoms and spin models

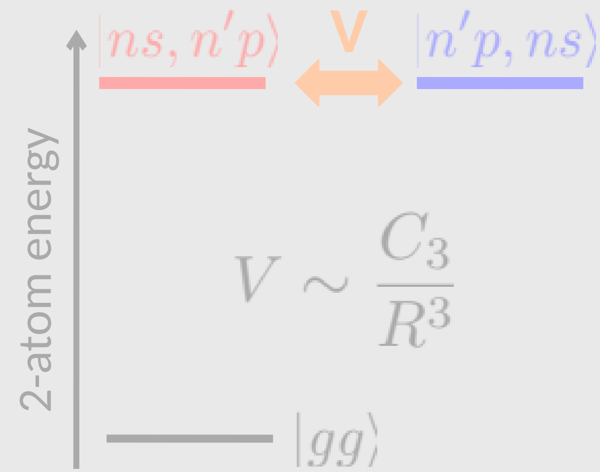


Browaeys & Lahaye, Nat.Phys. (2020)

van der Waals



Resonant dipole



Quantum Ising

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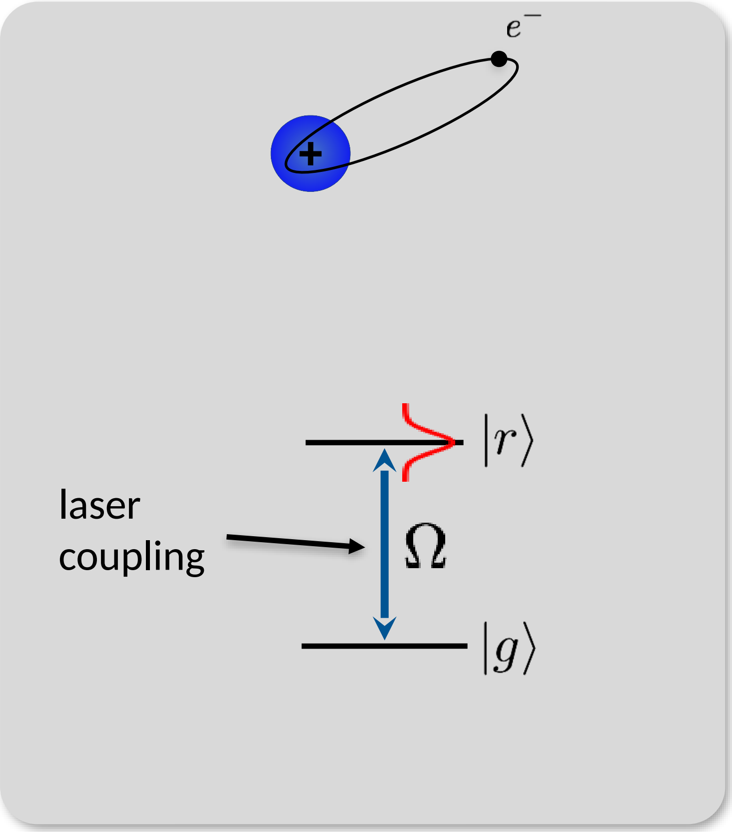
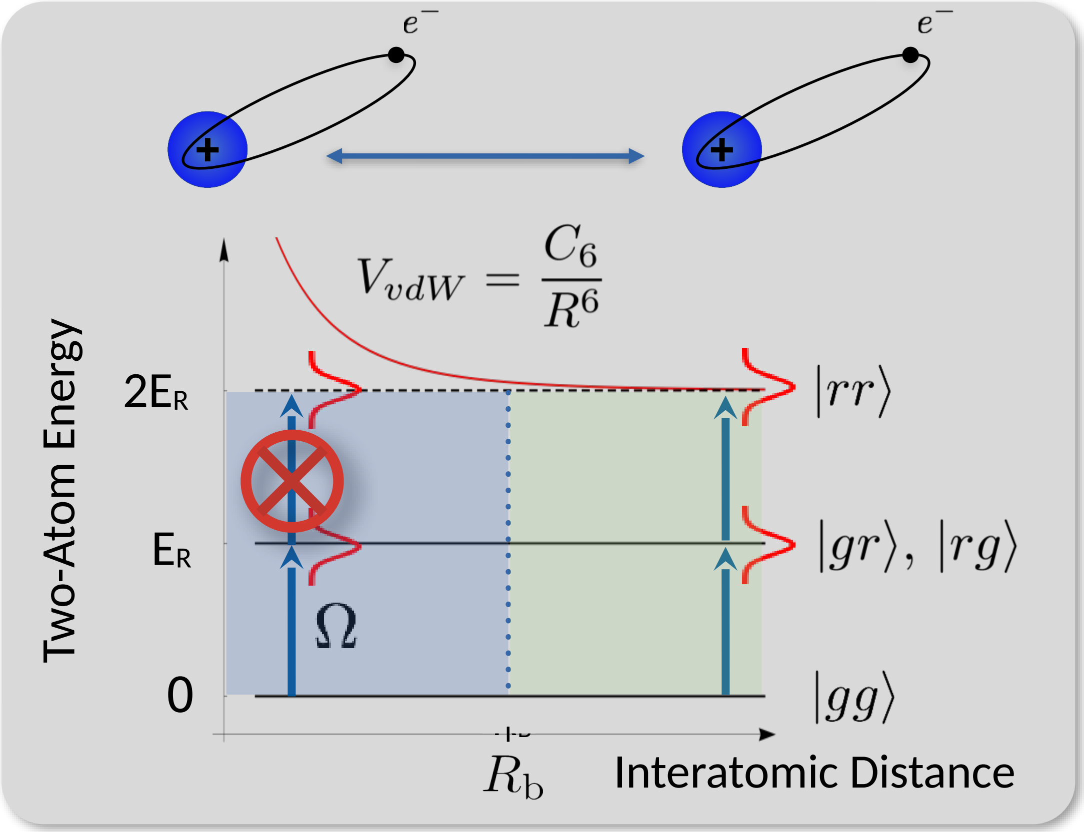
XY model

$$\hat{H} = \sum_{i \neq j} J_{ij} \left(\hat{\sigma}_i^+ \hat{\sigma}_j^- + \hat{\sigma}_i^- \hat{\sigma}_j^+ \right)$$

Van der Waals blockade

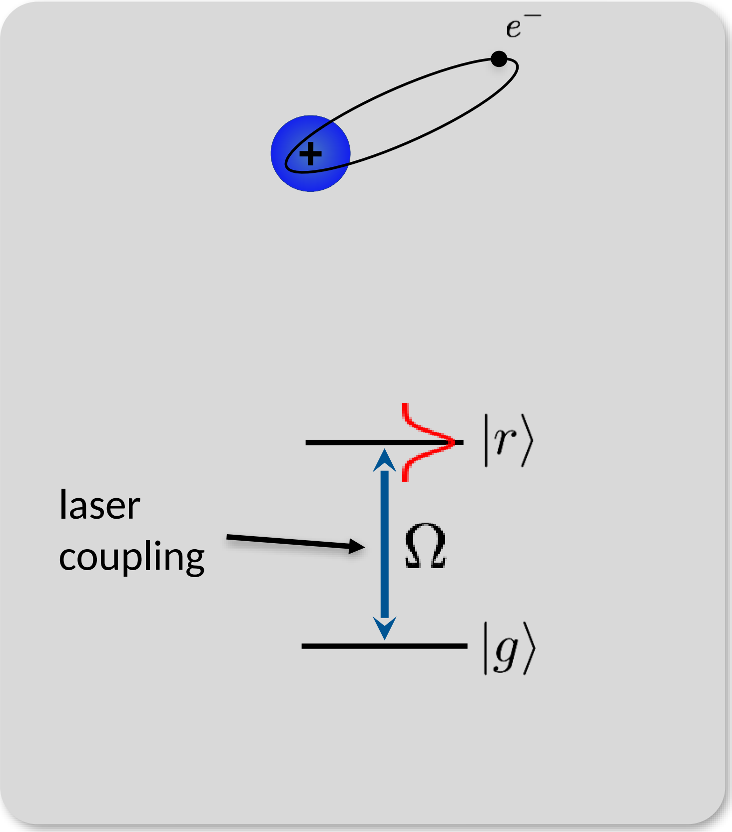


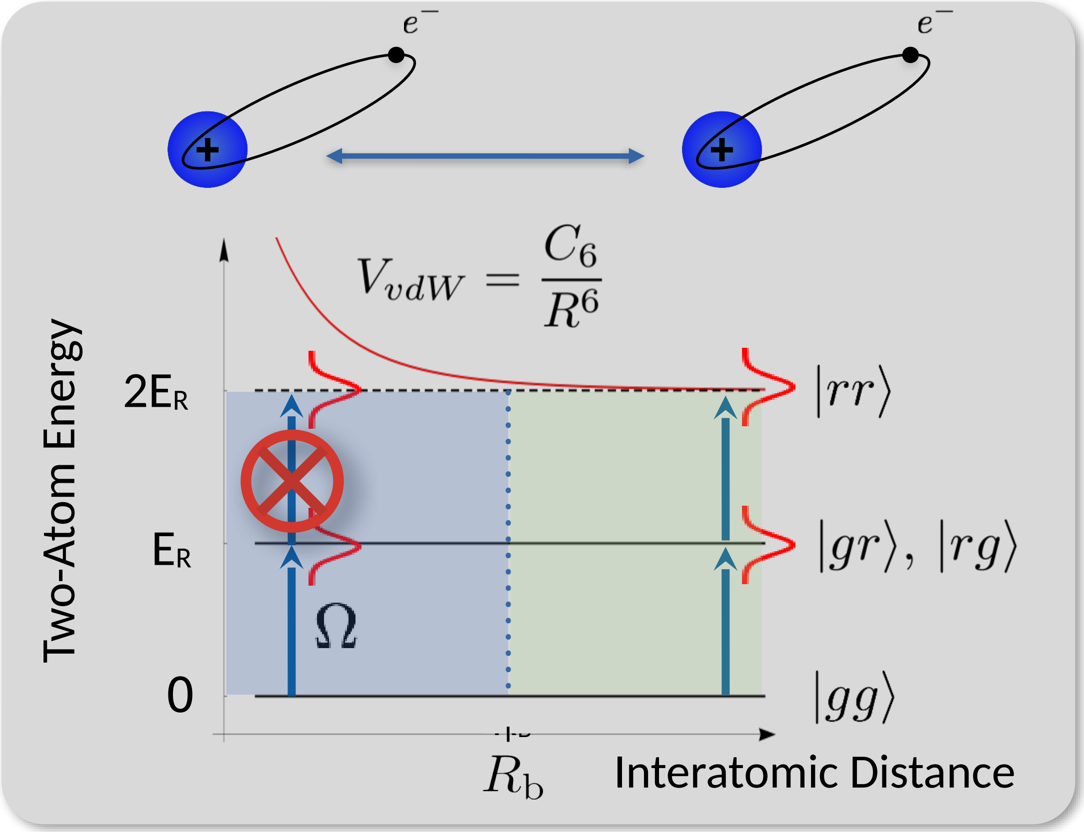


Jaksch *et al.*, PRL 2000
Lukin *et al.*, PRL 2001

Browaeys & Grangier,
Saffman, Nat. Phys. 2009

Van der Waals blockade





Blockade: $V_{vdW} \gg \hbar\Omega \implies |rr\rangle$ is not resonant.

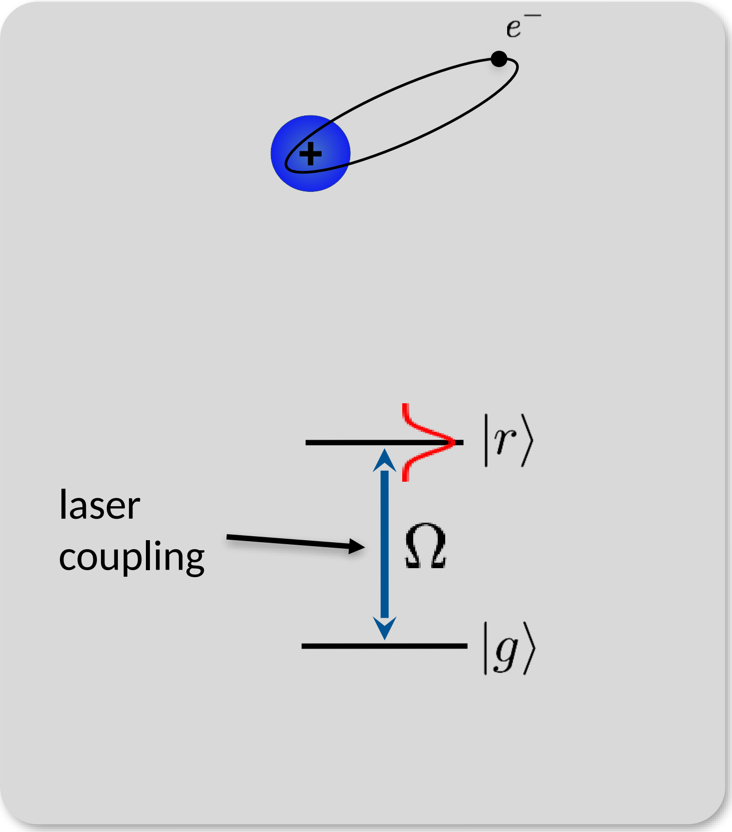
- No double excitation: $P_{rr} = 0$
- Enhanced coupling ($\sqrt{2}\Omega$) between $|gg\rangle$ and $\frac{1}{\sqrt{2}}(|gr\rangle + |rg\rangle)$

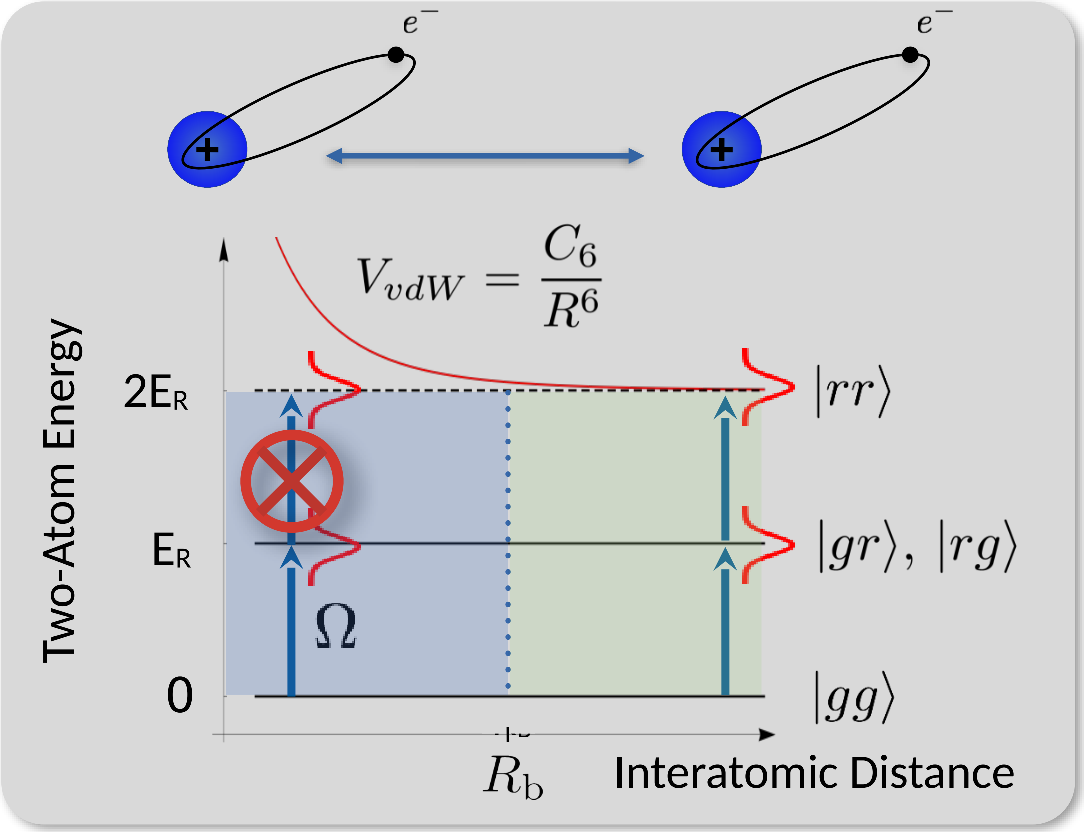
Jaksch *et al.*, PRL 2000
Lukin *et al.*, PRL 2001

Browaeys & Grangier,
Saffman, Nat. Phys. 2009

Entanglement!

Van der Waals blockade





Blockade: $V_{vdW} \gg \hbar\Omega$

- No double excitation: $P_{rr} = 0$
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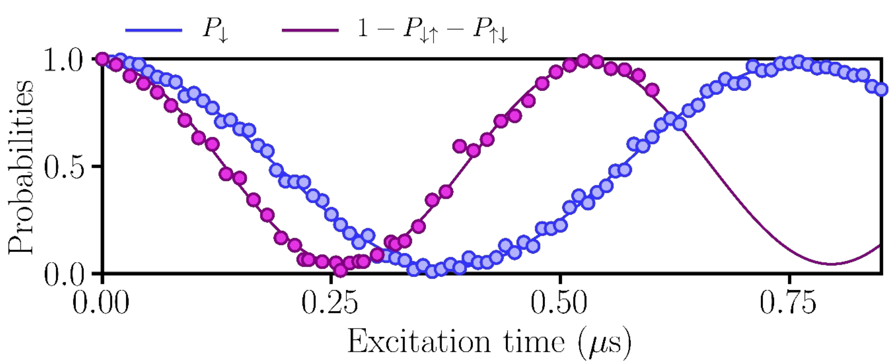
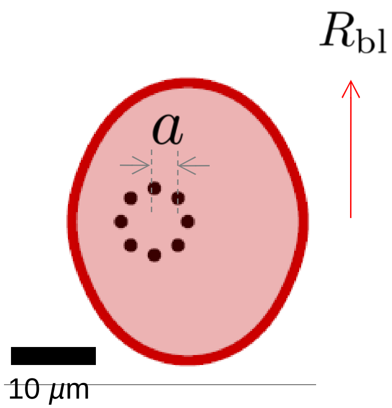
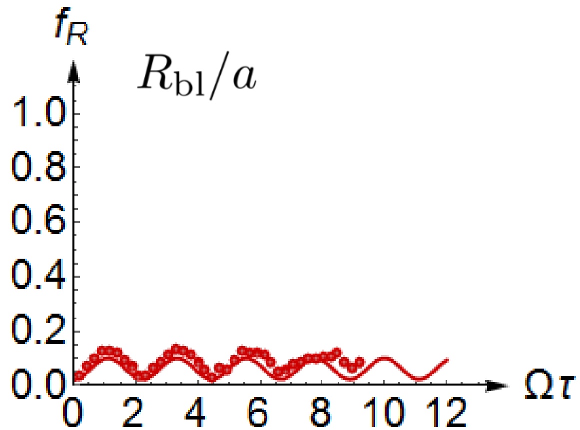


Jaksch *et al.*, PRL 2000
Lukin *et al.*, PRL 2001

Browaeys & Grangier,
Saffman, Nat. Phys. 2009

Excitation dynamics, varying the blockade radius



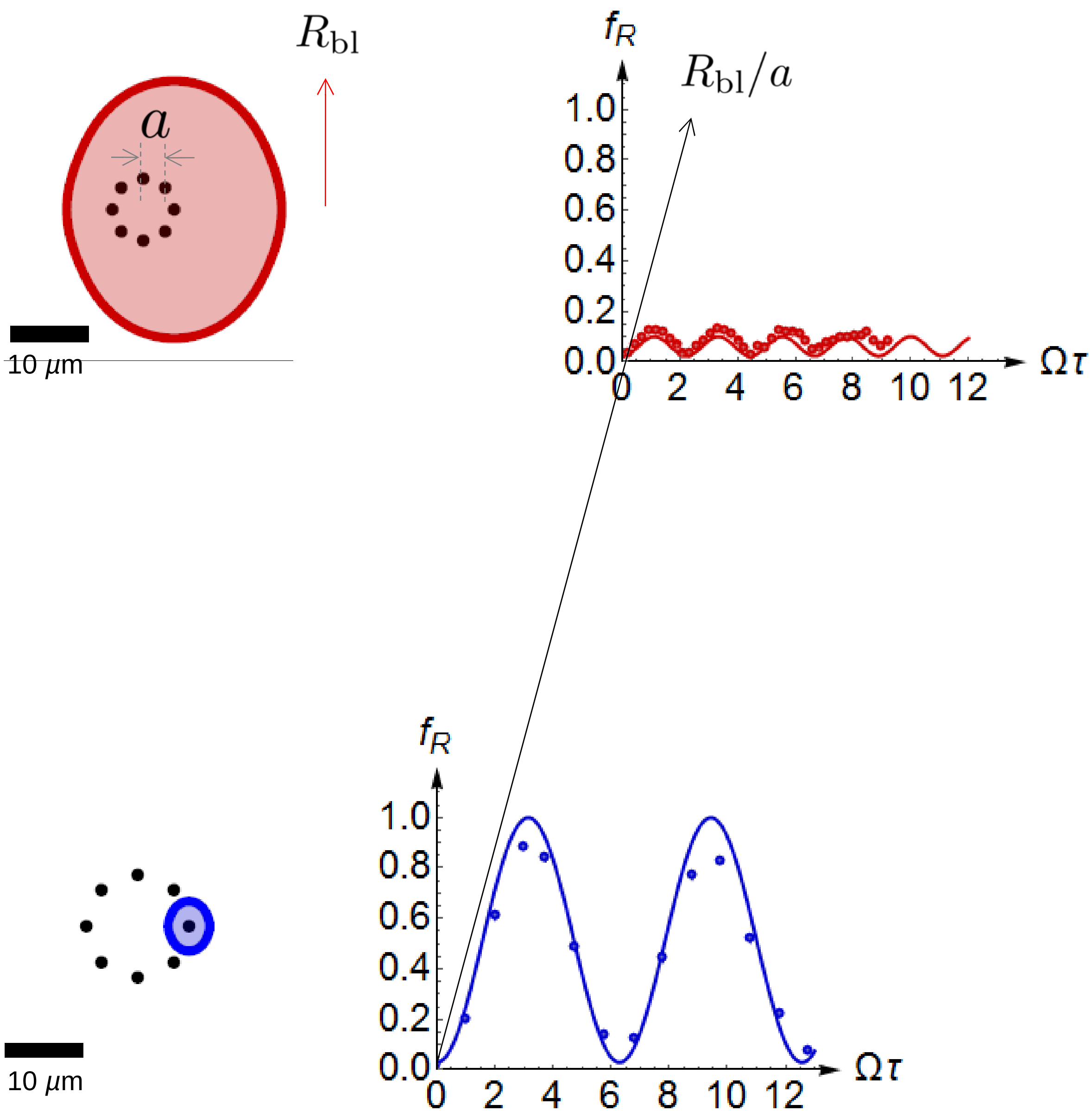


Full blockade:

Oscillations at $\sqrt{N}\Omega$

$$f_{\rm R}^{\rm max} = 1/N$$

Excitation dynamics, varying the blockade radius



Full blockade:

Oscillations at $\sqrt{N}\Omega$

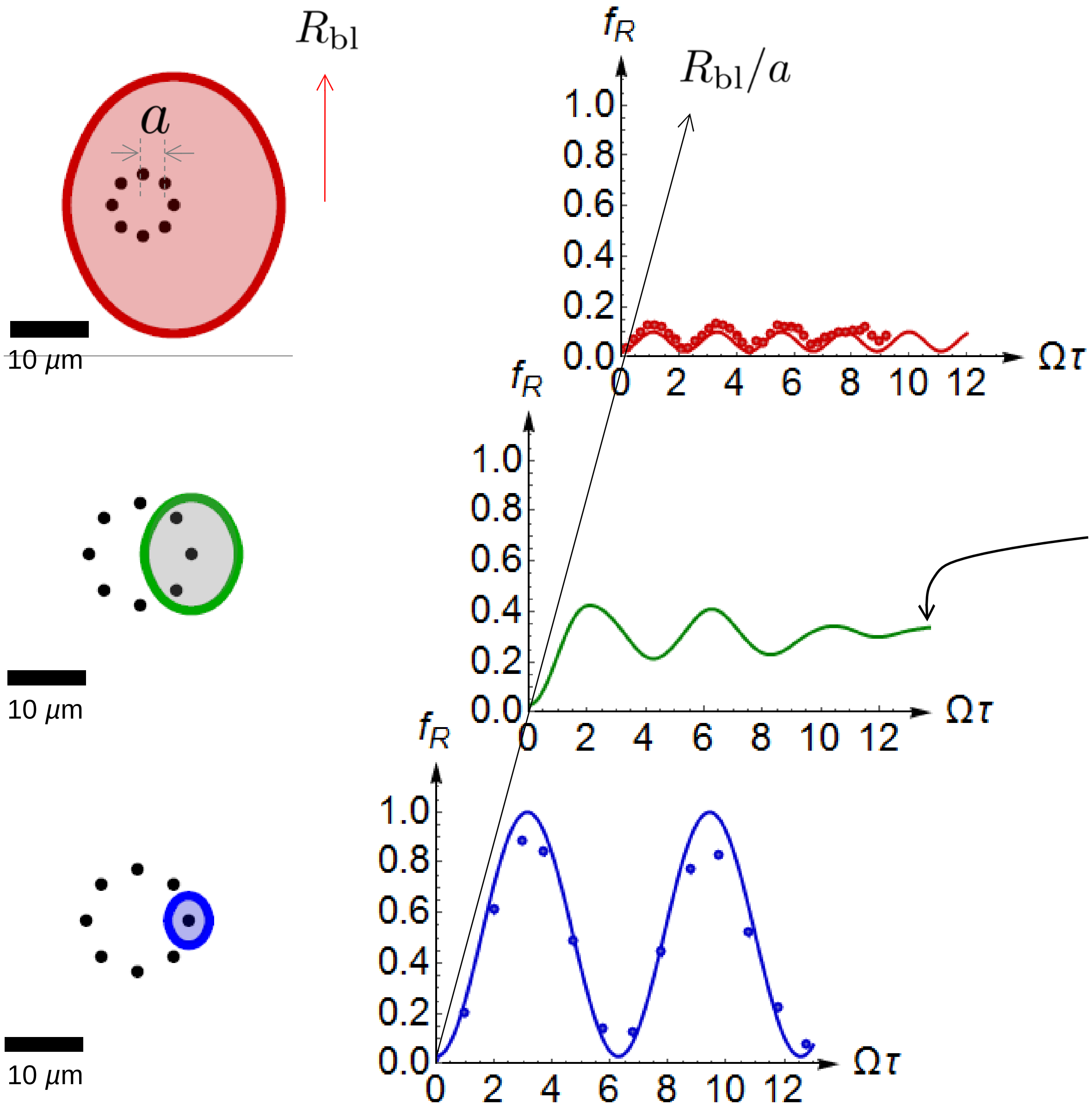
$f_R^{max} = 1/N$

Independent atoms:

Oscillations at Ω

$f_R^{max} = 1$

Excitation dynamics, varying the blockade radius



Full blockade:

Oscillations at $\sqrt{N}\Omega$

$$f_{\rm R}^{\rm max} = 1/N$$

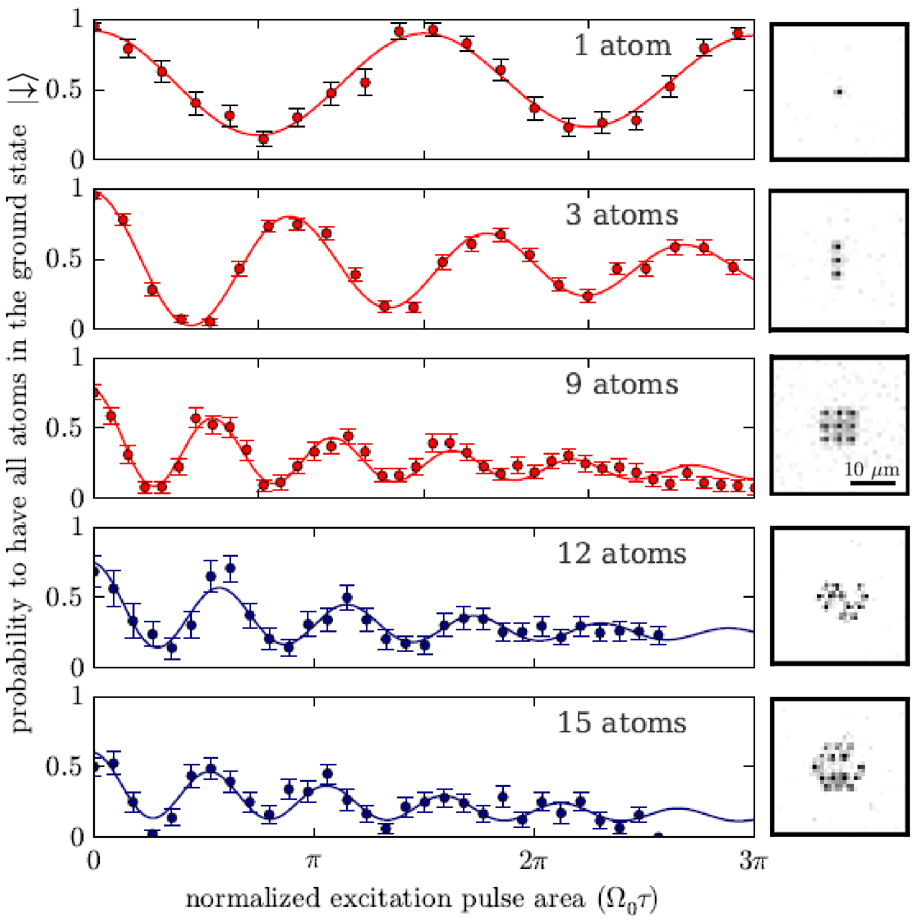
Dynamics?

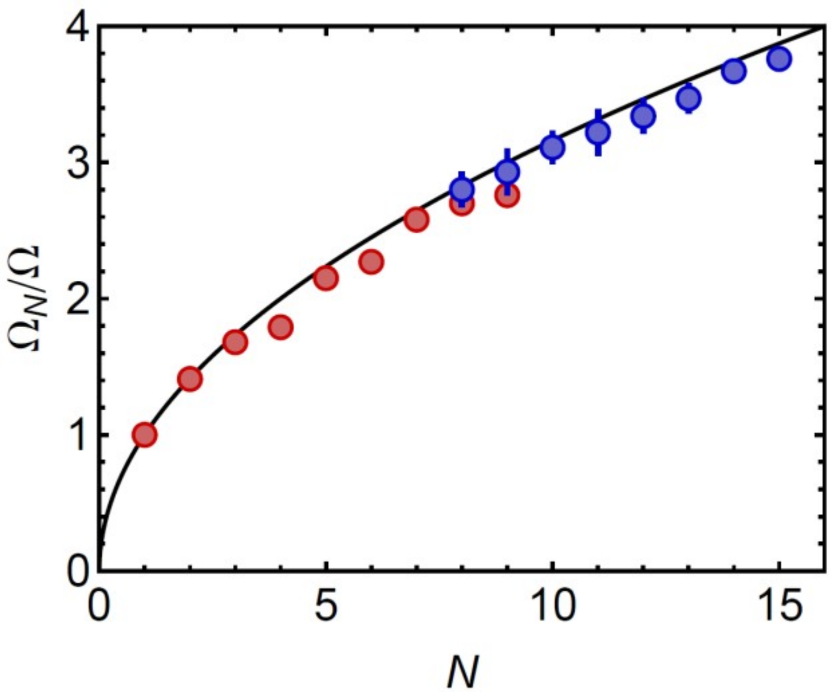
Independent atoms:

Oscillations at Ω

$$f_{\rm R}^{\rm max} = 1$$

Full blockade with many atoms





Also: Saffman, Kuzmich, Bloch, Pfau, Ott…

Some references to Rydberg physics and QS

“Rydberg atoms”, T. Gallagher, Cambridge (1994).

“An experimental and theoretical guide to strongly interacting Rydberg gases”, R. Loew, J. Phys. B **45**, 113001(2012).

“Quantum Information with Rydberg atoms”, M. Saffman, T. Walker, K. Moelmer, Rev. Mod. Phys. **82**, 2313 (2010).

Special Issue on Rydberg Atomic Physics, J. Phys. B (2016) contains many reviews:

“Experimental investigations of the dipolar interactions between a few individual Rydberg atoms”, A. Browaeys, D. Barredo, and T. Lahaye, J. Phys. B **49**, 152001 (2016).

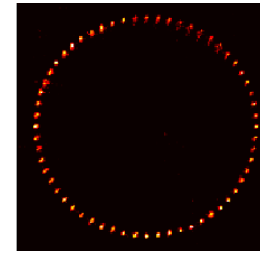
“Quantum simulation and computing with Rydberg-interacting qubits”, M. Morgado, S. Whitlock, AVS Quantum Sci. **3**, 023501 (2021).

“Many-body physics with individually controlled Rydberg atoms“, A. Browaeys and T. Lahaye, Nat. Phys. **16**, 132 (2020).

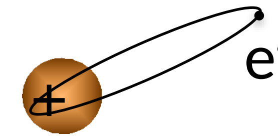
Questions?

Outline

1. **Arrays of individual atoms**



2. **Rydberg atoms and their interactions**



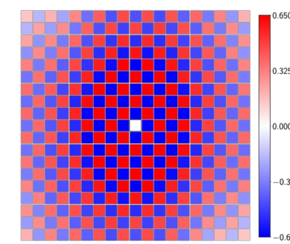
3. **Examples of quantum simulations**

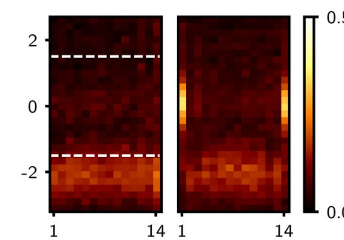
   A. Exploration of phase diagrams

   B. Out-of-Equilibrium dynamics

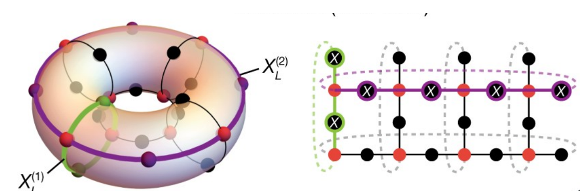
   C. Ground state preparation & squeezing

   D. Synthetic Topological matter





4. **Digital quantum computing**



Outline

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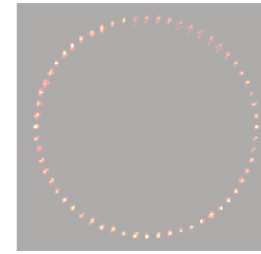
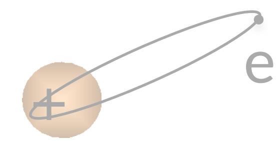
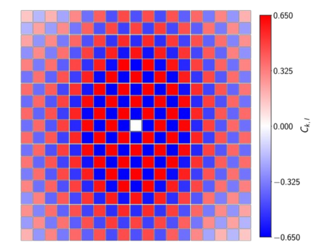


2. **Rydberg atoms and their interactions**

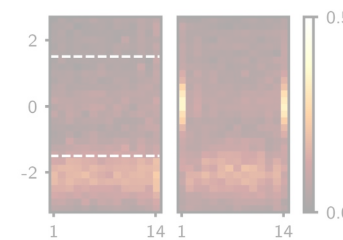


3. **Examples of quantum simulations**

   A. Exploration of phase diagrams



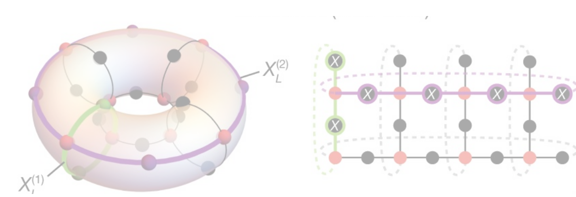
   B. Out-of-Equilibrium dynamics



   C. Ground state preparation & squeezing

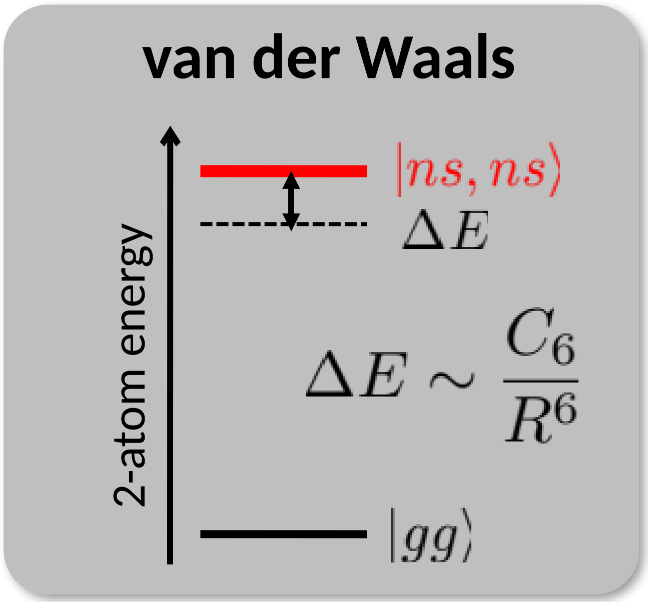
   D. Synthetic Topological matter

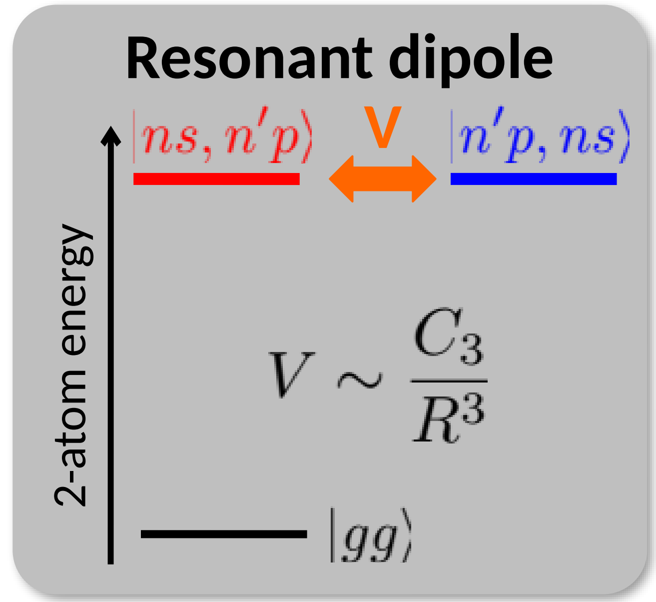
4. **Digital quantum computing**



Interactions between Rydberg atoms and spin models

Browaeys & Lahaye, Nat.Phys. (2020)





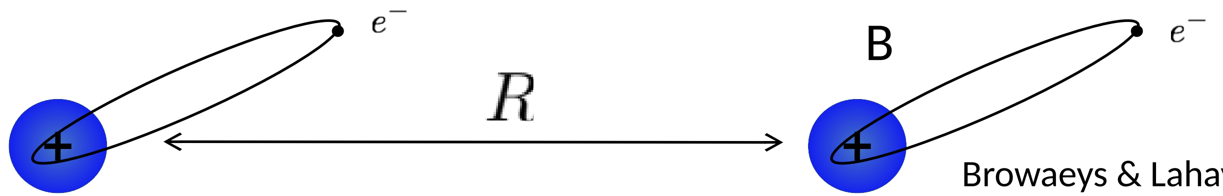
Quantum Ising

$$\hat{H} = \sum_{i \neq j} J_{ij} \hat{\sigma}_z^{(i)} \hat{\sigma}_z^{(j)}$$

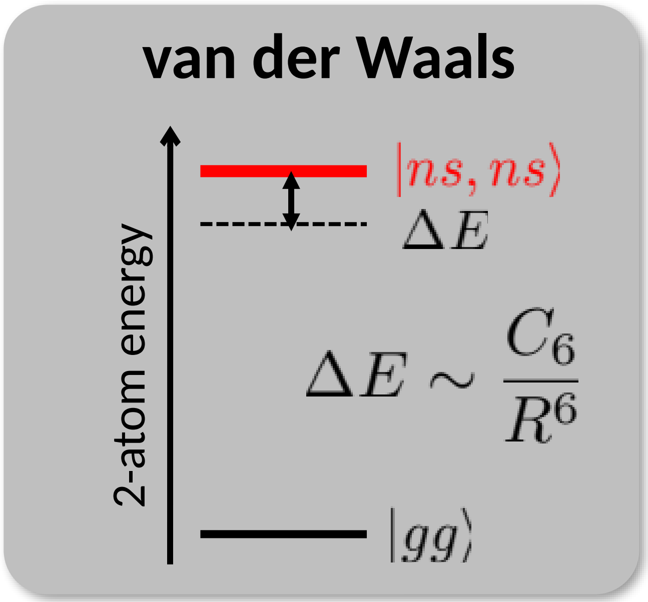
XY model

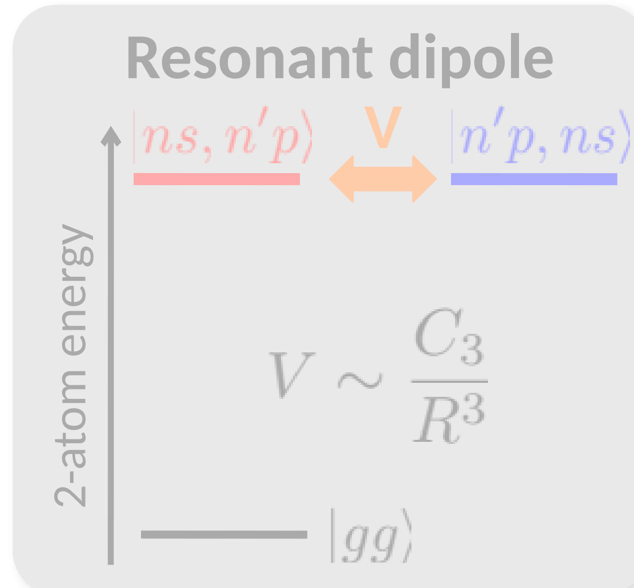
$$\hat{H} = \sum_{i \neq j} J_{ij} \left(\hat{\sigma}_i^+ \hat{\sigma}_j^- + \hat{\sigma}_i^- \hat{\sigma}_j^+ \right)$$

Interactions between Rydberg atoms and spin models



Browaeys & Lahaye, Nat.Phys. (2020)





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XY model

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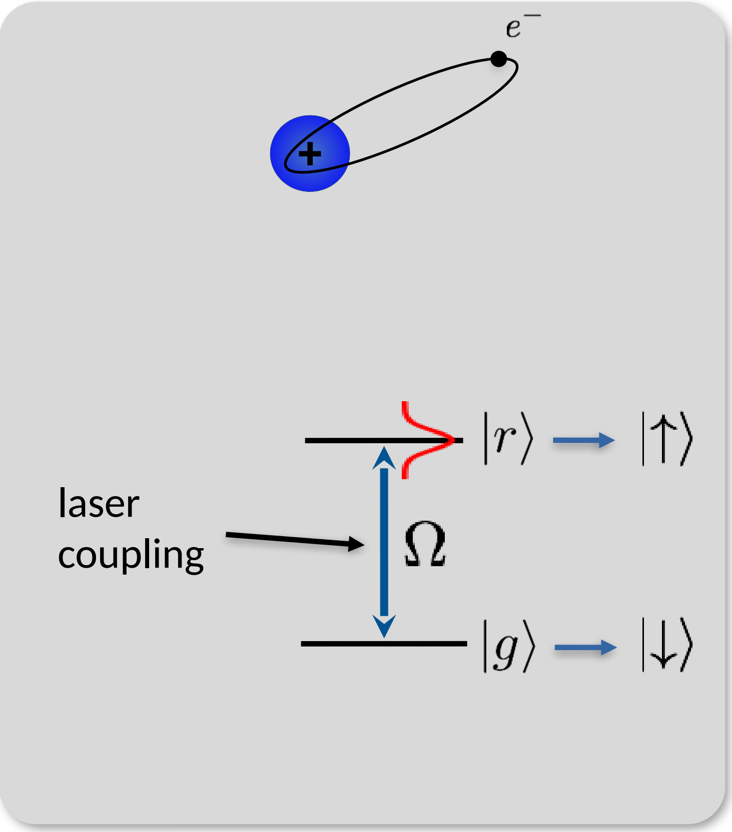
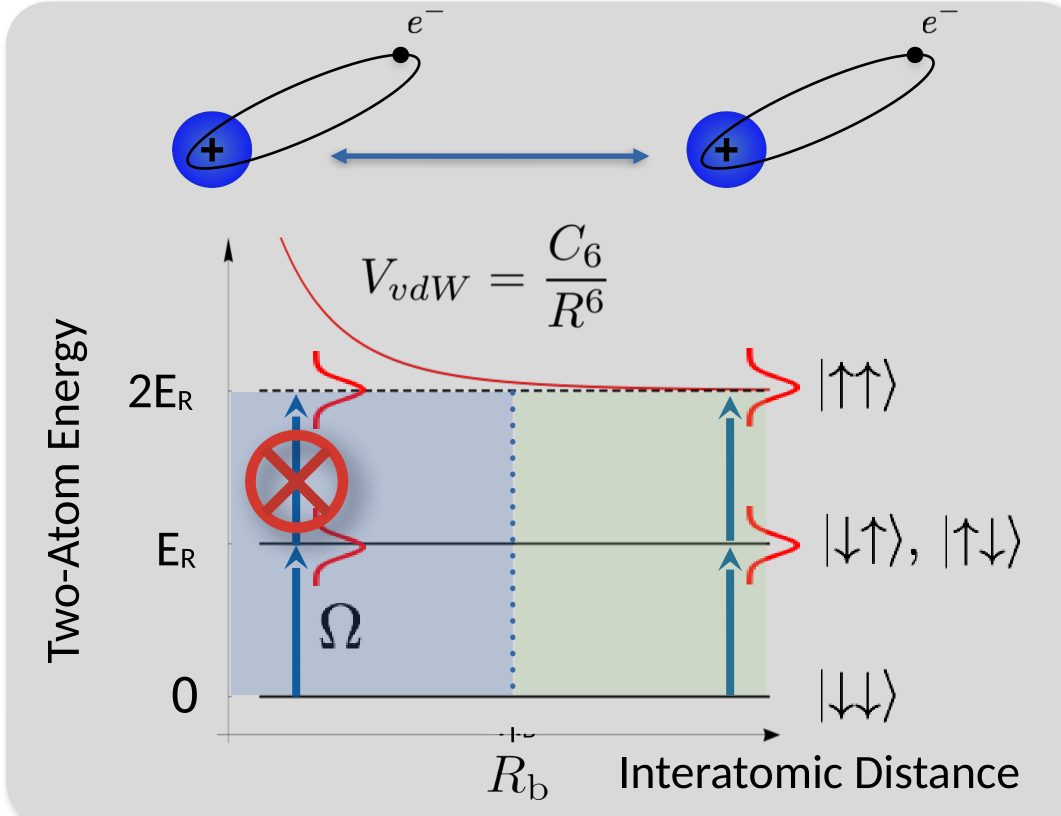
From van der Waals to Ising

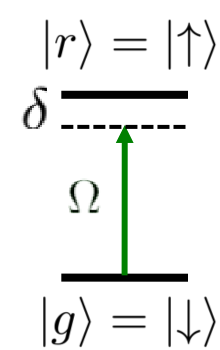




Quantum Ising model:

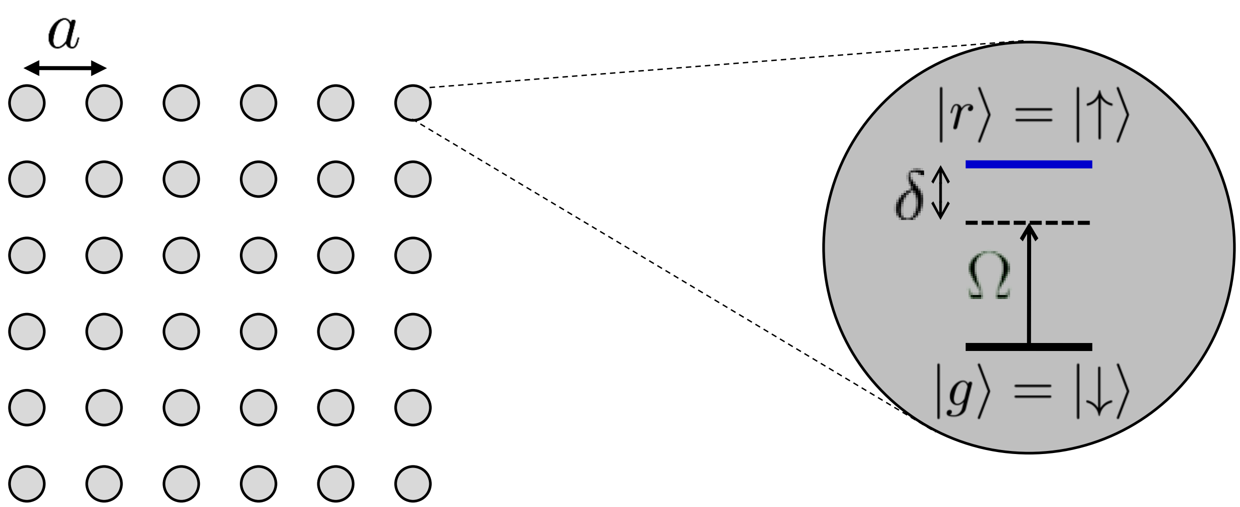
$$H = \frac{\hbar\Omega}{2}\sum_i \sigma_x^i + \hbar\delta\sum_i \hat{n}_i + \sum_{i<j}\frac{C_6}{R_{ij}^6}\hat{n}_i\hat{n}_j$$

Transverse B ***Longitudinal B*** ***Spin-spin interaction***



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

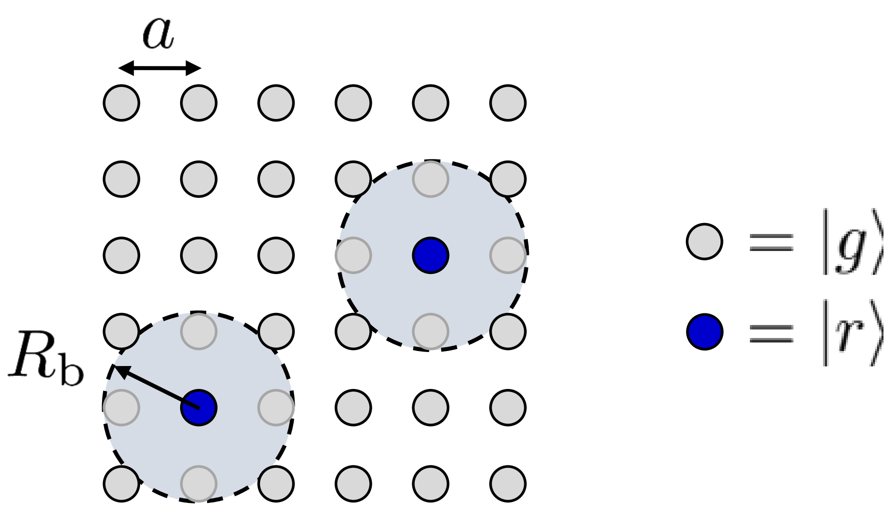
Rydberg blockade and anti-ferromagnetic order



Rydberg blockade and anti-ferromagnetic order

$$R_\mathrm{b} \sim a \qquad \frac{C_6}{a^6} \sim \Omega$$

Nearest-neighbor blockade

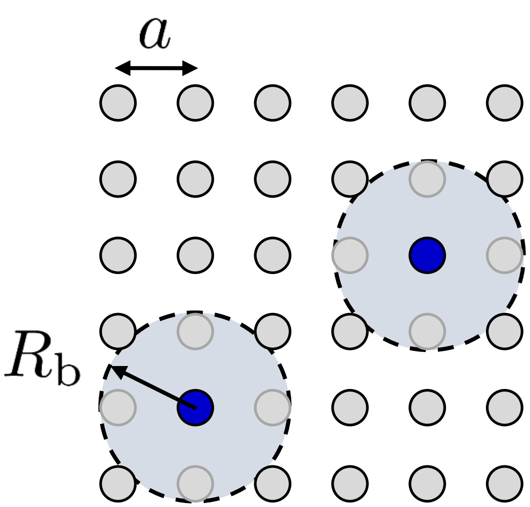


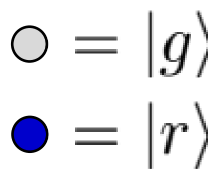
Rydberg blockade and anti-ferromagnetic order

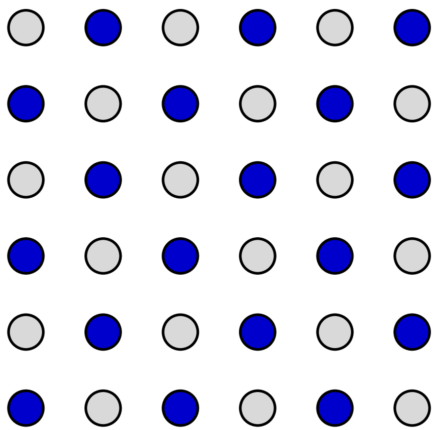
$$R_\mathrm{b} \sim a \qquad \frac{C_6}{a^6} \sim \Omega$$

Nearest-neighbor blockade

Antiferromagnetic ground state







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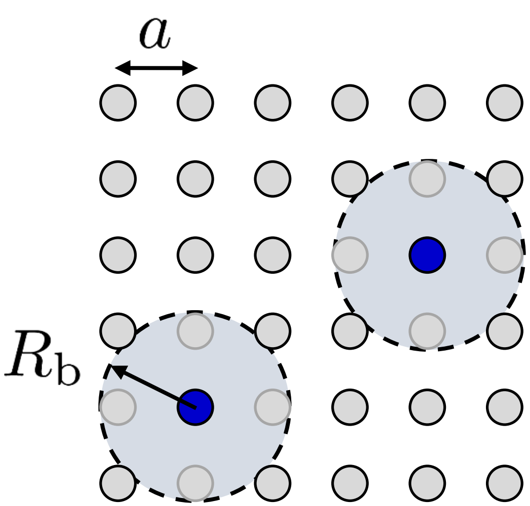
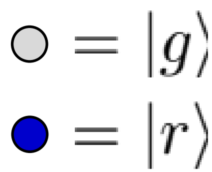
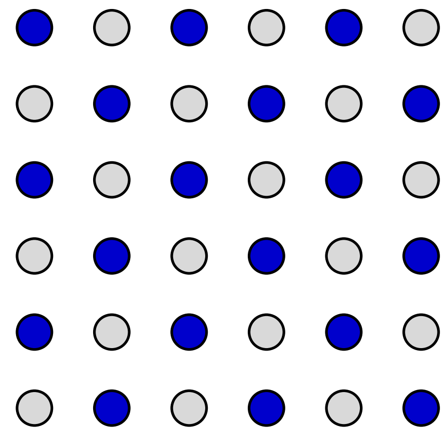
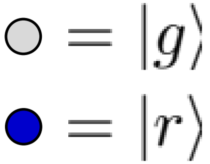


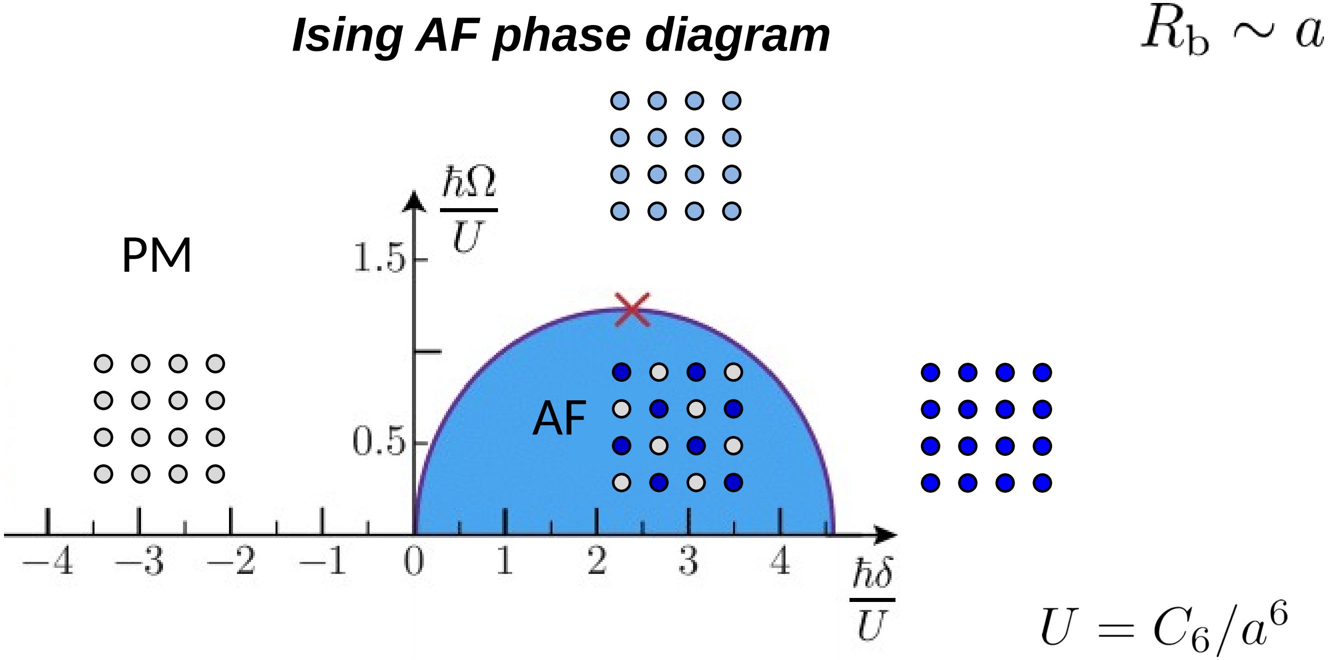


Antiferromagnetic ground state

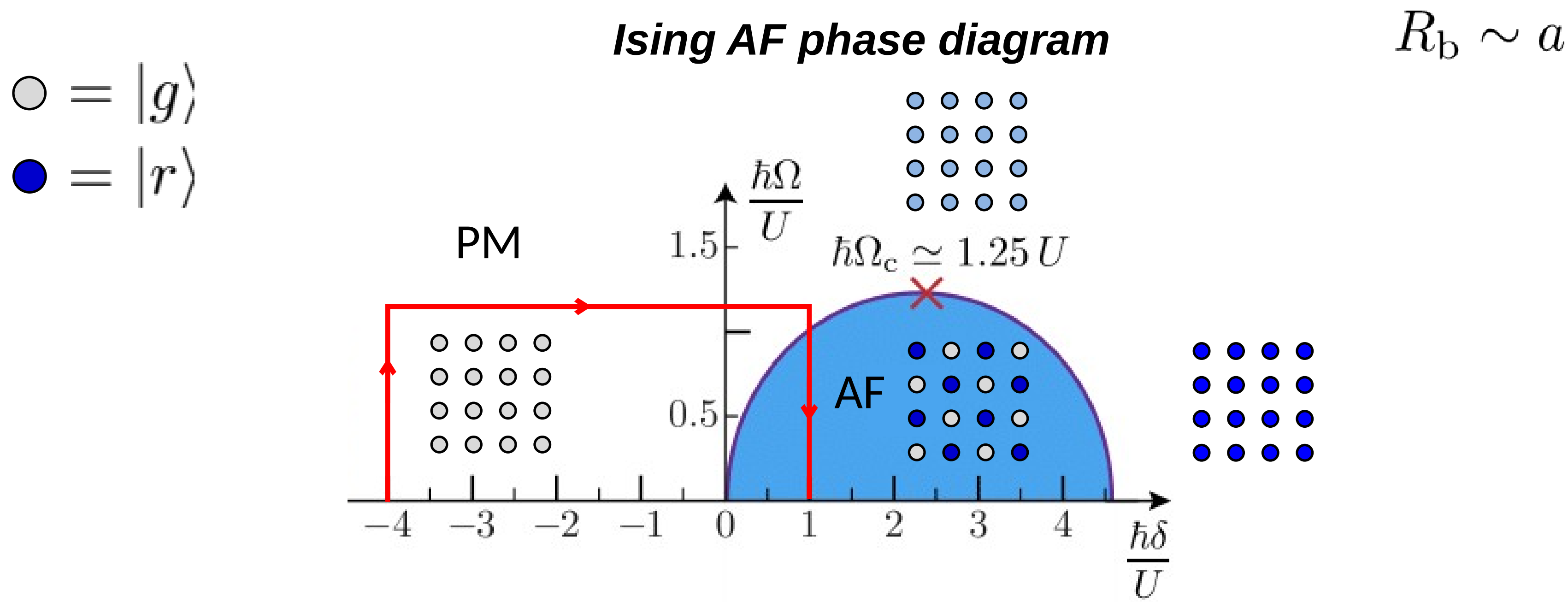


Phase diagram on a square lattice

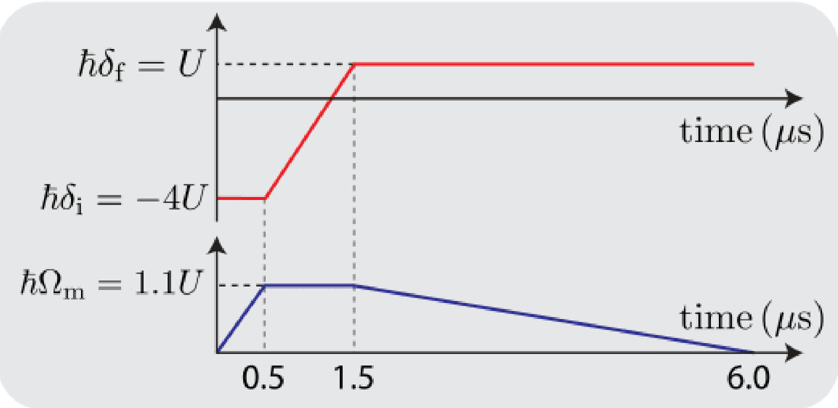




Probing anti-ferromagnetic order on a square lattice



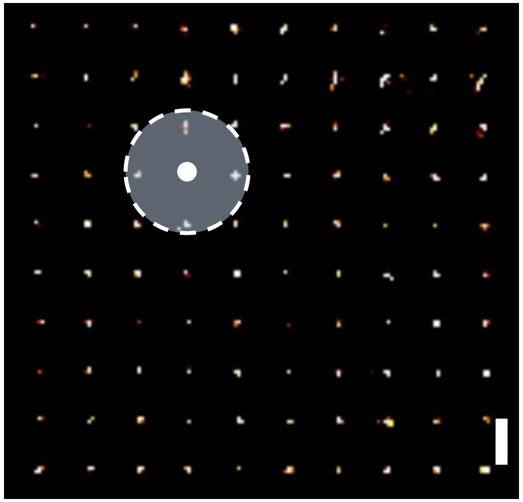
$$H = \sum_i \left(\frac{\hbar\Omega(t)}{2}\sigma_x^i - \hbar\delta(t)\hat{n}_i \right) + \sum_{i<j} \frac{C_6}{R_{ij}^6}\hat{n}_i\hat{n}_j$$



Vary Rabi frequency and detuning to explore the phase diagram

Preparation of a 2D Ising anti-ferromagnet on a square

10×10 square array



a=10 μm

1D: Pohl **PRL** 2010; Bloch **Science** 2015; Lukin **Nature** 2017, 2019;
2D: Lienhard **PRX** 2018, Bakr **PRX** 2018; Lukin **Nature** 2021

Preparation of a 2D Ising anti-ferromagnet on a square

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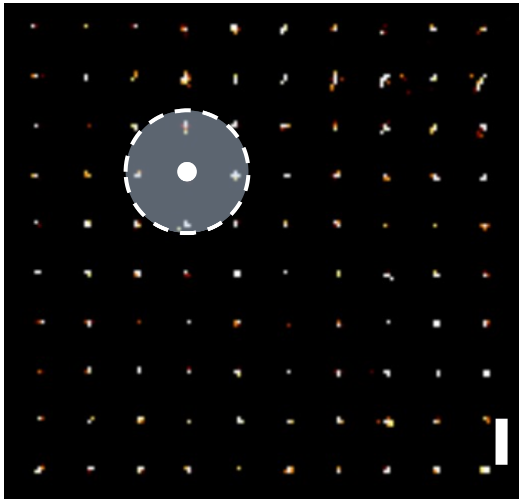
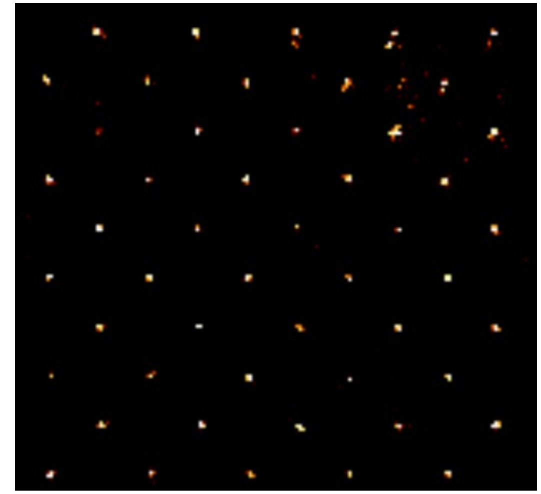


a=10 µm

sweep

n=75S

Perfect AF (Néel) ordering!

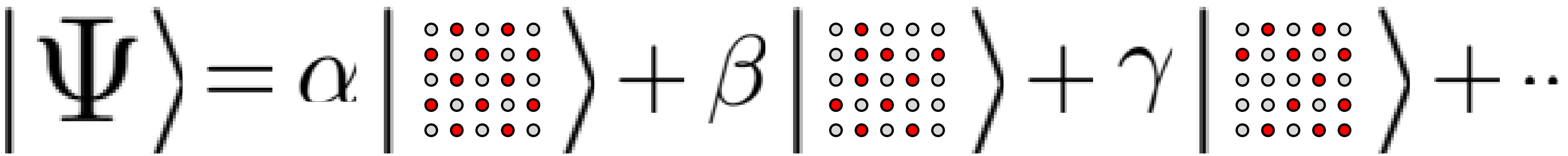


Missing atoms = Rydberg

1D: Pohl **PRL** 2010; Bloch **Science** 2015; Lukin **Nature** 2017, 2019;
2D: Lienhard **PRX** 2018, Bakr **PRX** 2018; Lukin **Nature** 2021

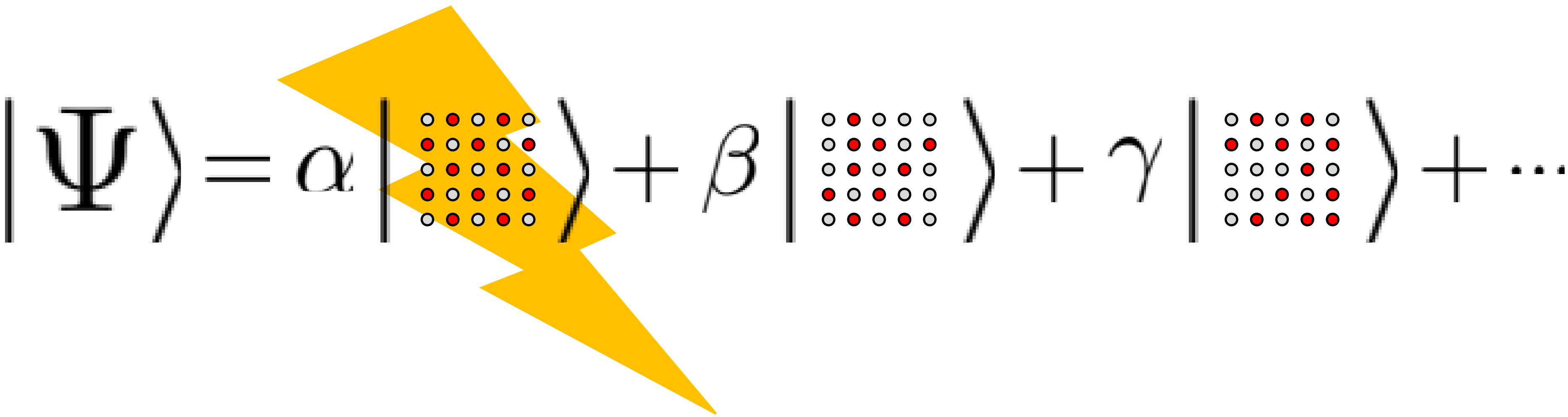
Seeing the many-body wavefunction

At the end of experiment:



Seeing the many-body wavefunction

At the end of experiment:

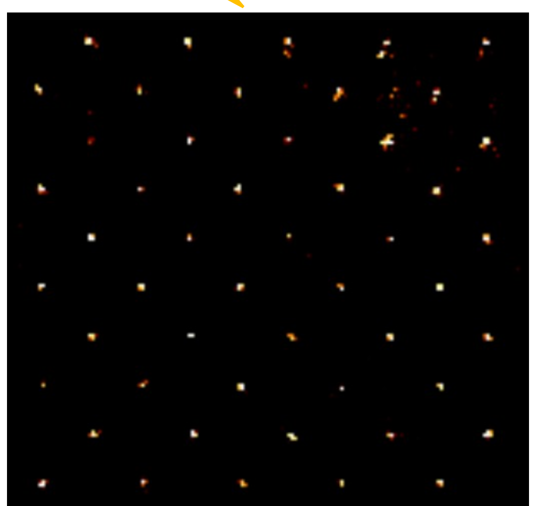


Seeing the many-body wavefunction

At the end of experiment:

$$|\Psi\rangle = \alpha|\ \rangle + \beta|\ \rangle + \gamma|\ \rangle + \cdots$$

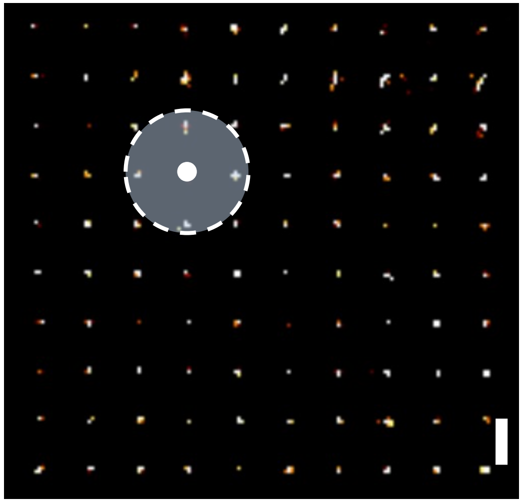
$$|\Psi_f\rangle =$$



probability $|\alpha|^2$

Preparation of a 2D Ising anti-ferromagnet on a square

10×10 square array



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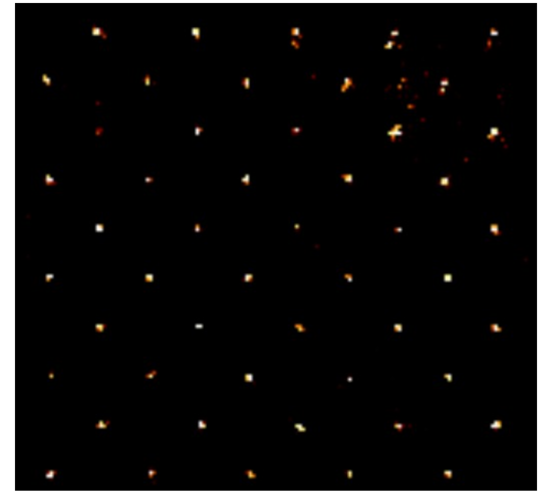
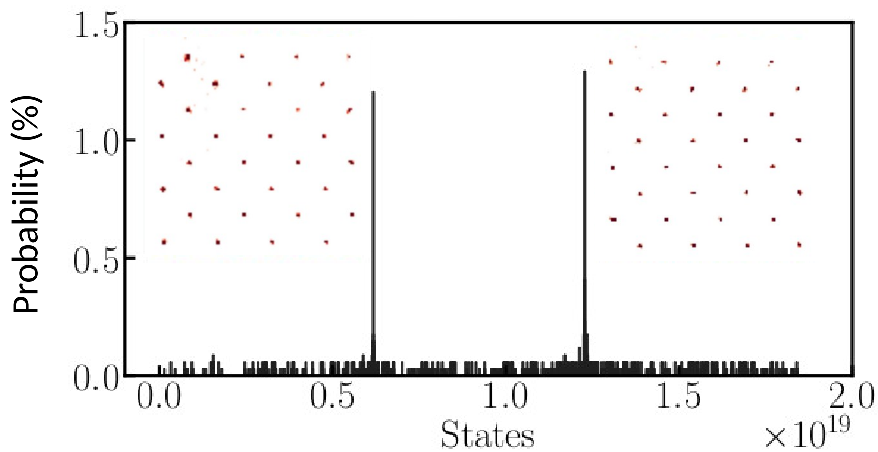


Missing atoms = Rydberg

(8x8)



1D: Pohl **PRL** 2010; Bloch **Science** 2015; Lukin **Nature** 2017, 2019;
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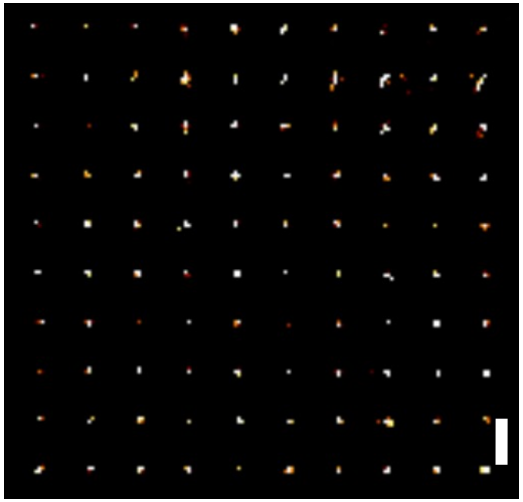
Preparation of a 2D Ising anti-ferromagnet on a square

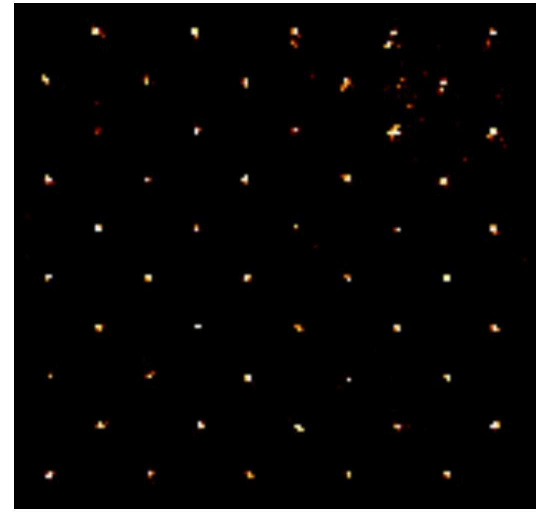
10×10 square array



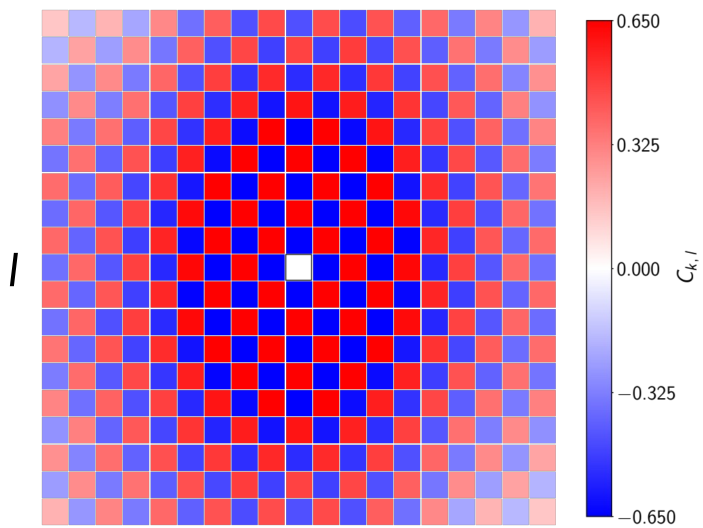
a=10 μm

sweep

n=75S



$$C_{kl} \sim \langle n_k n_l \rangle - \langle n_k \rangle \langle n_l \rangle$$

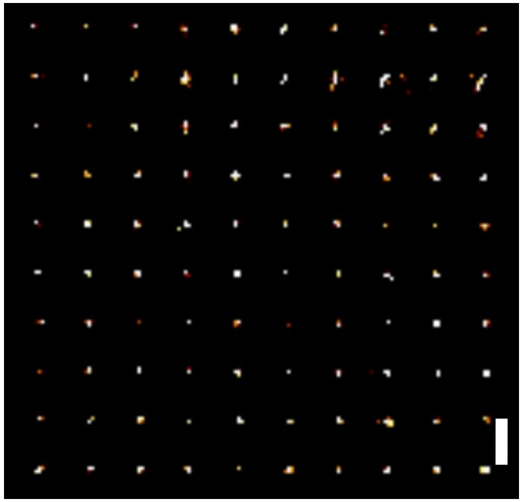


Scholl *et al.*, Nature **595**, 233 (2021)

Also: Ebadi *et al.*, Nature **595**, 227 (2021)

Preparation of a 2D Ising anti-ferromagnet on a square

10×10 square array



a=10 µm

sweep

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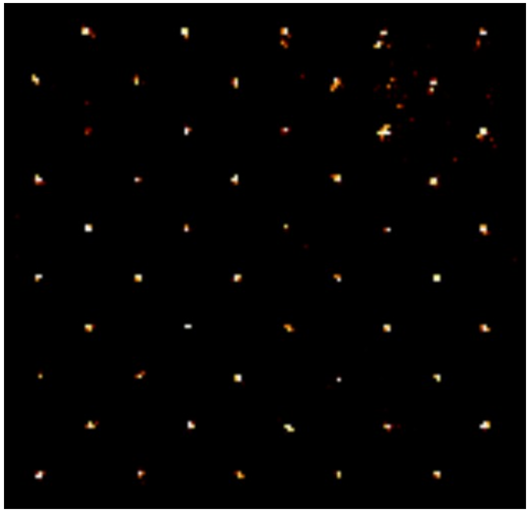

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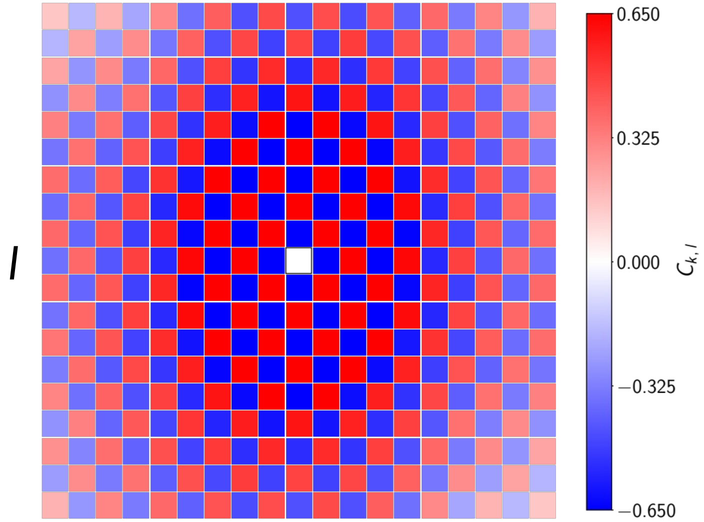
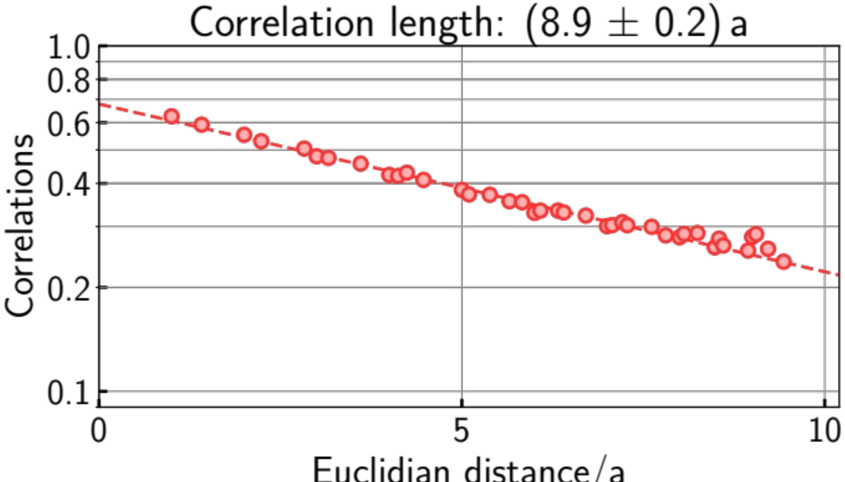


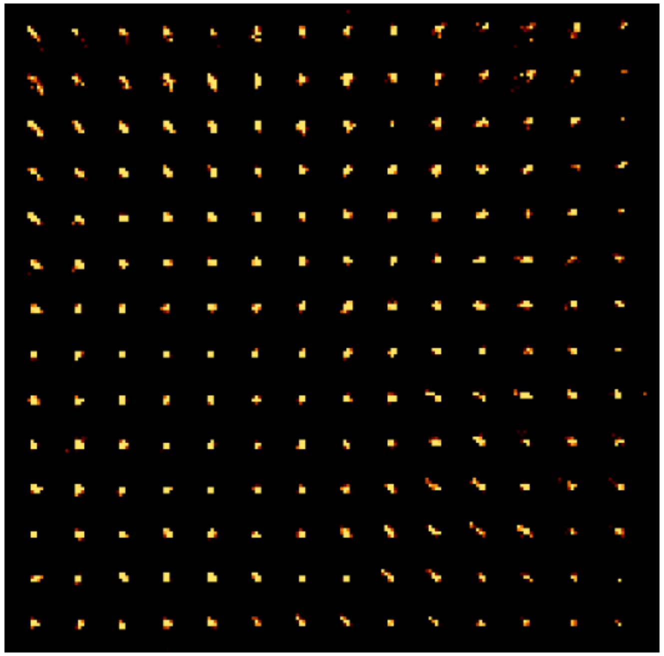


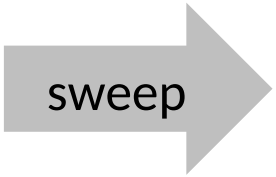
Scholl *et al.*, Nature **595**, 233 (2021)

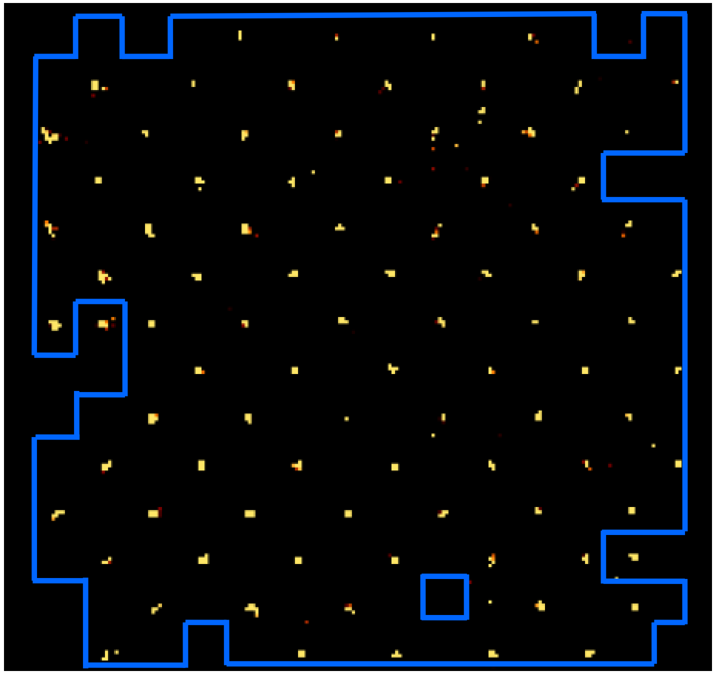
Also: Ebadi *et al.*, Nature **595**, 227 (2021)

Preparation of a 2D Ising anti-ferromagnet on a square

14x14 square array





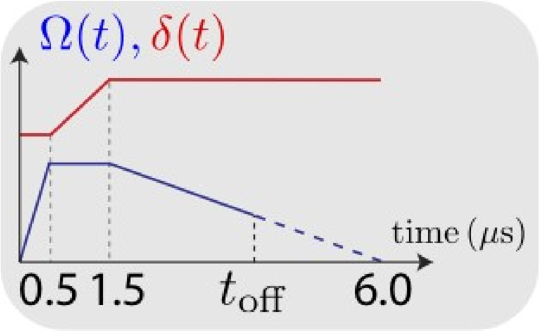


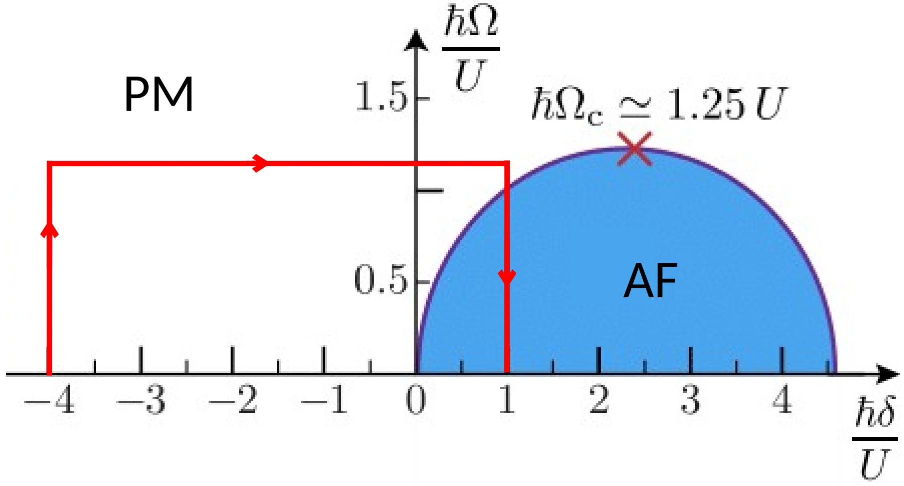
182-atom antiferromagnetic cluster!

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

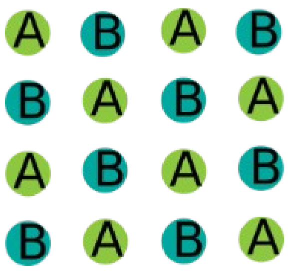
Also: Ebadi *et al.*, Nature **595**, 227 (2021)

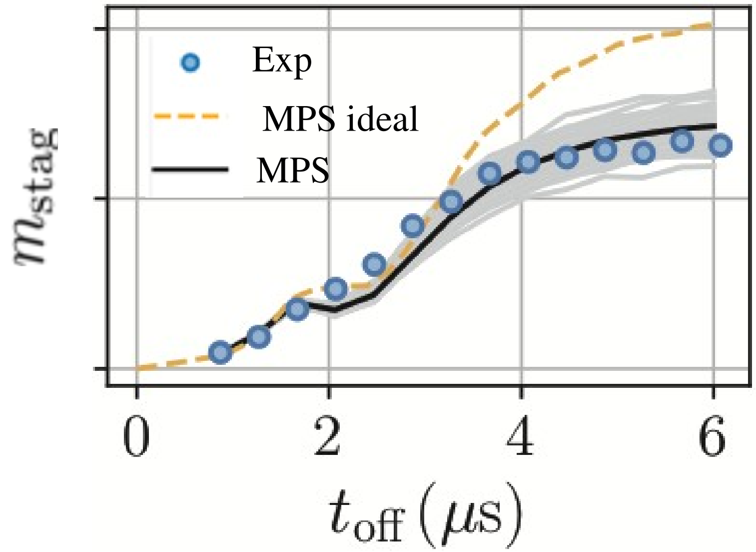
Benchmarking the dynamics on a square





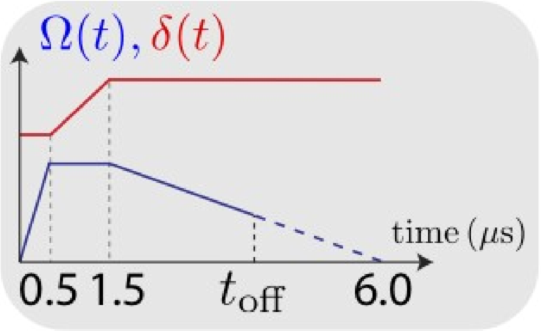
Staggered magnetisation: $m_{\rm stag} = \langle |n_A - n_B| \rangle$

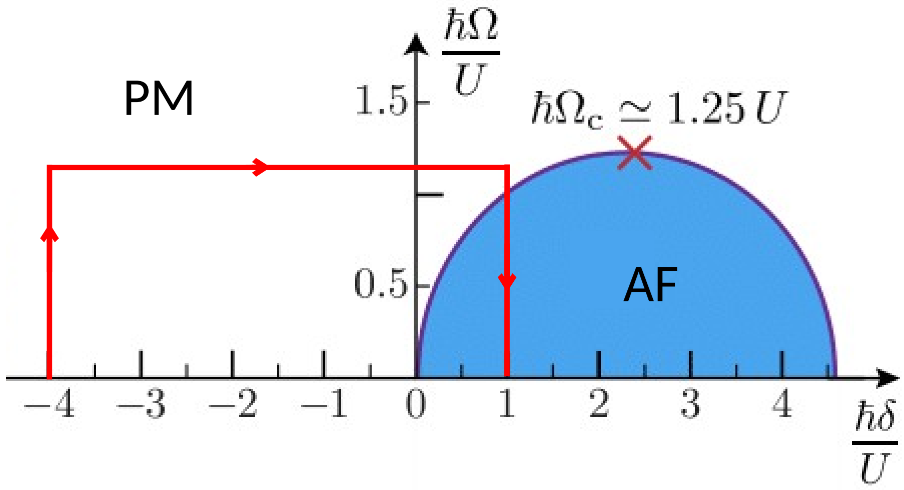




Including experimental imperfections: $U_{ij}, \Omega_i, \delta_i$, real ramp...

Benchmarking the dynamics on a square





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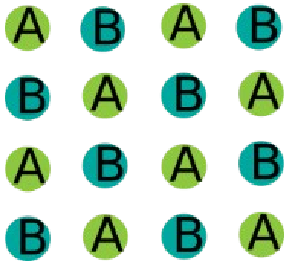
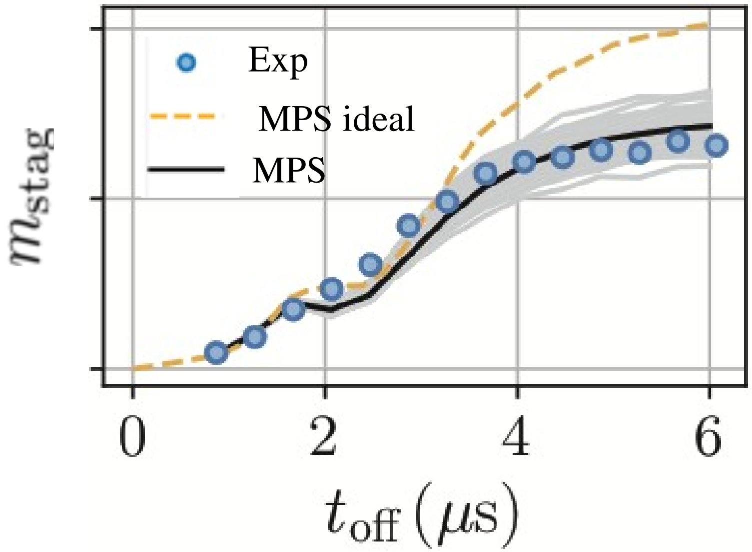
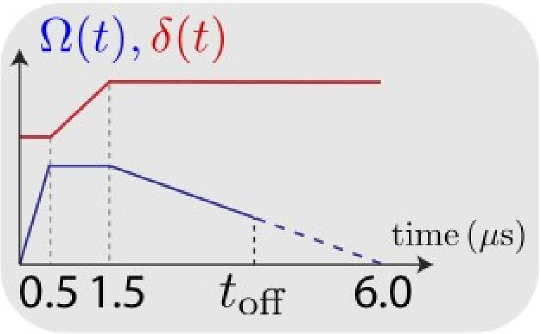
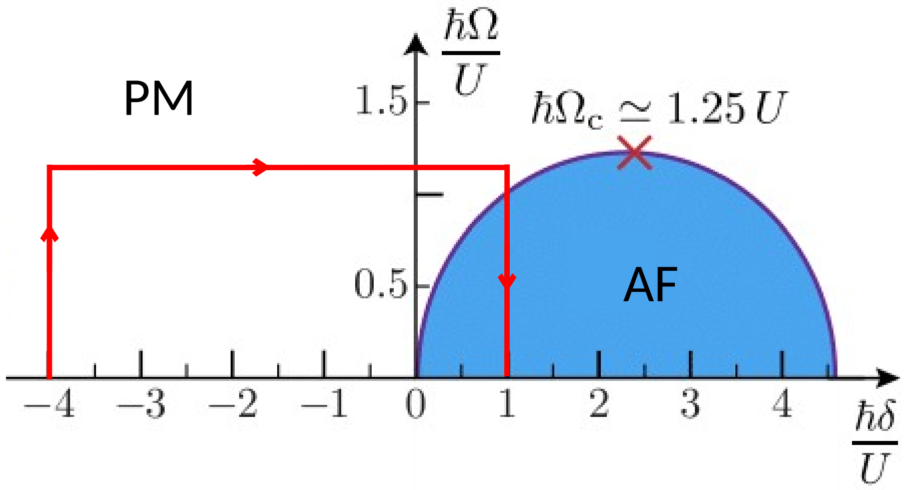




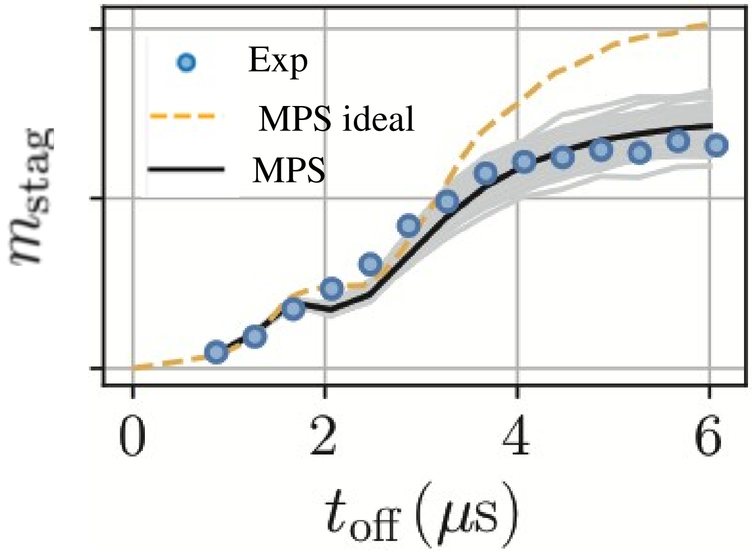
Accurate MPS limited to 10 x 10 (14 days!!)

Including experimental imperfections: $U_{ij}, \Omega_i, \delta_i$, real ramp…





Tutorial about this!

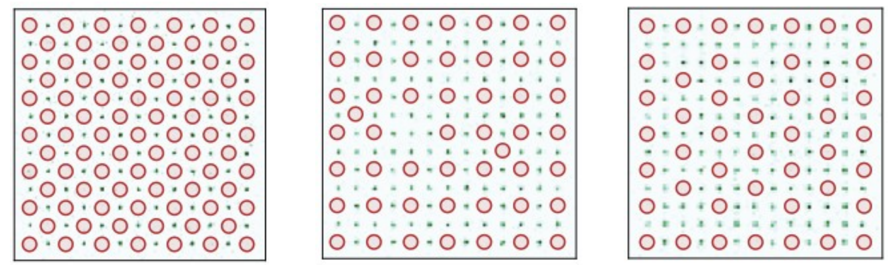


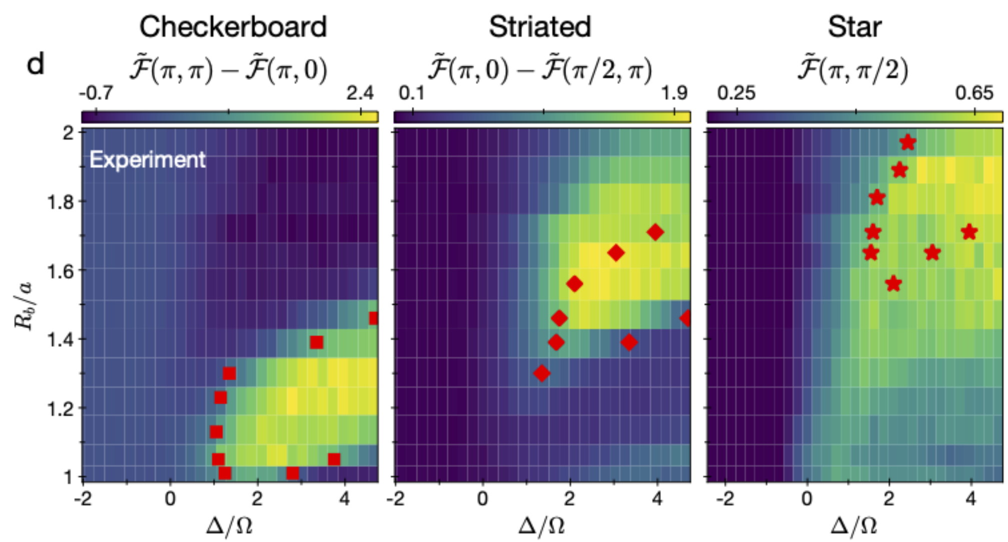
Accurate MPS limited to 10 x 10 (14 days!!)

2D Ising anti-ferromagnet on a square beyond NN interactions

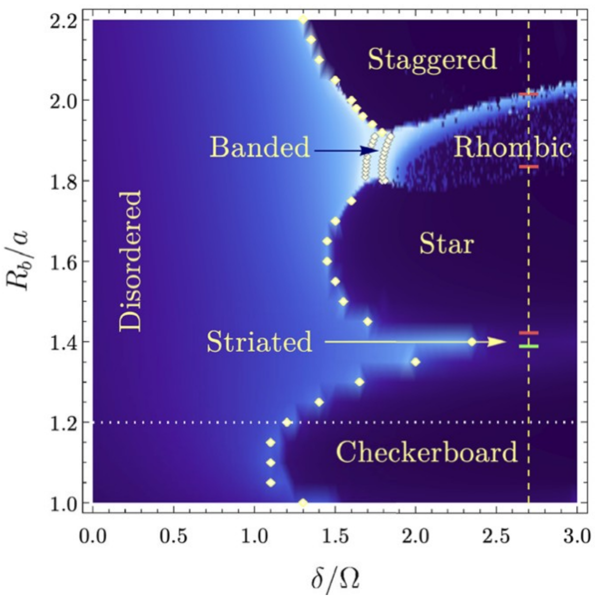
Lukin group

Ebadi, Nature **595**, 227 (2021)





Vary $(C_6/a^6)/\Omega$



Samajdar *et al.* PRL (2020)

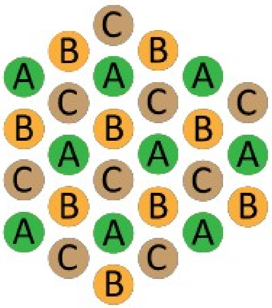
Order parameters:

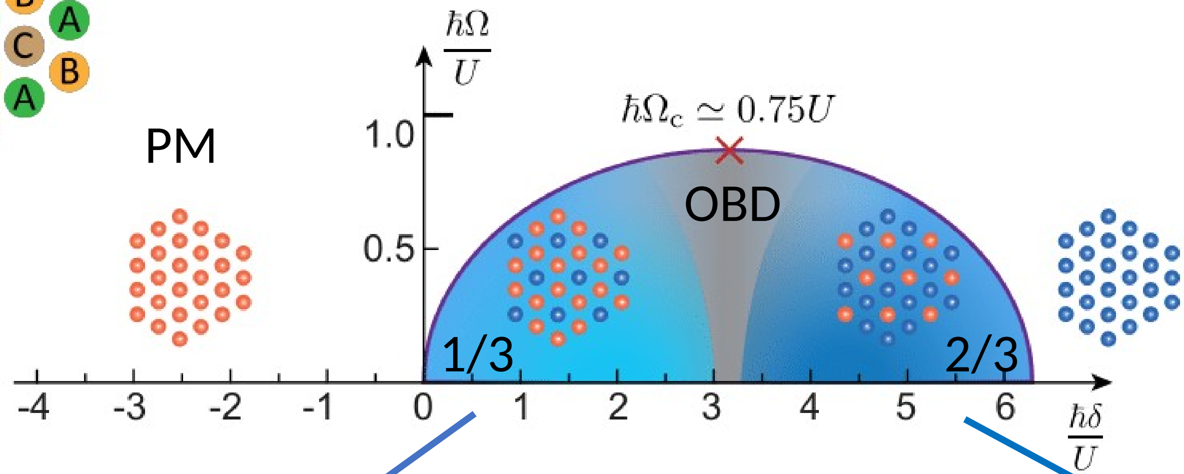
$$\mathcal{F}(\mathbf{k}) = \frac{1}{\sqrt{N}} \sum_i n_i \, e^{i\mathbf{k}\cdot\mathbf{x}_i}$$

2D Ising anti-ferromagnet on triangular lattices

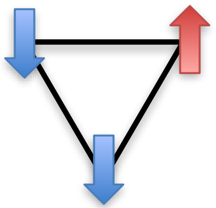
$R_b \sim a$

Ising AF phase diagram on triangle

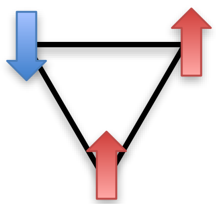




1/3 phase:



2/3 phase:

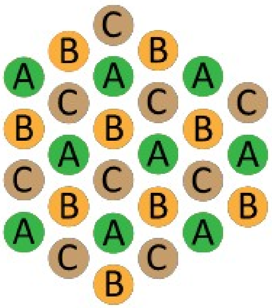


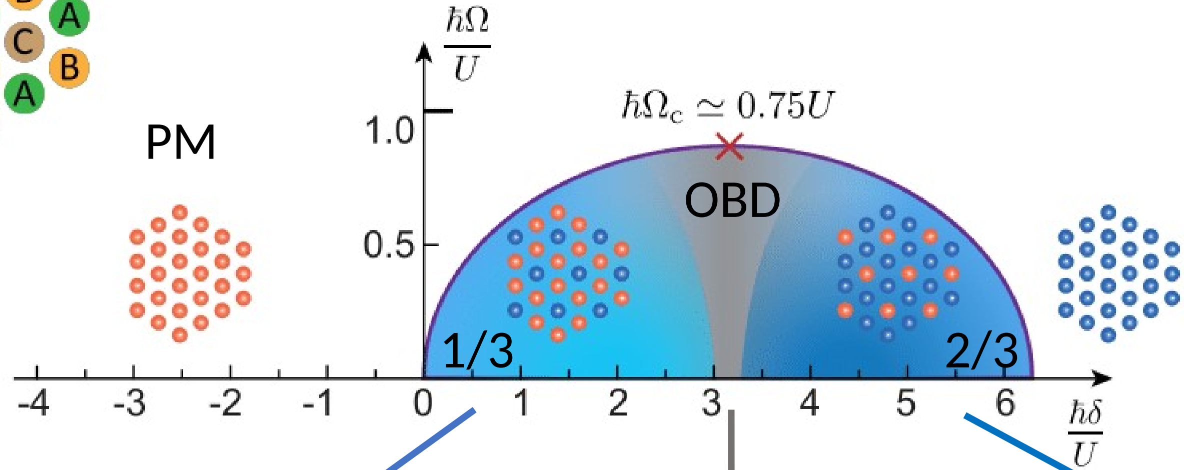
Classical phases

2D Ising anti-ferromagnet on triangular lattices

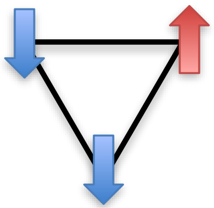
Ising AF phase diagram on triangle

$R_{\rm b} \sim a$

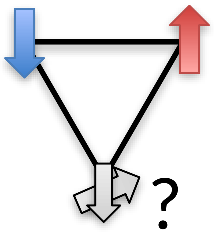




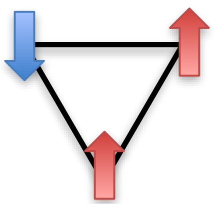
1/3 phase:



'Order-by-disorder' phase:

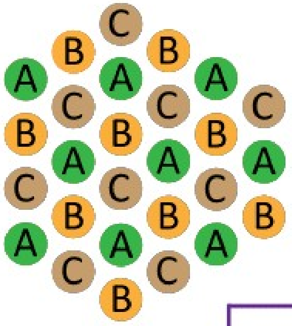


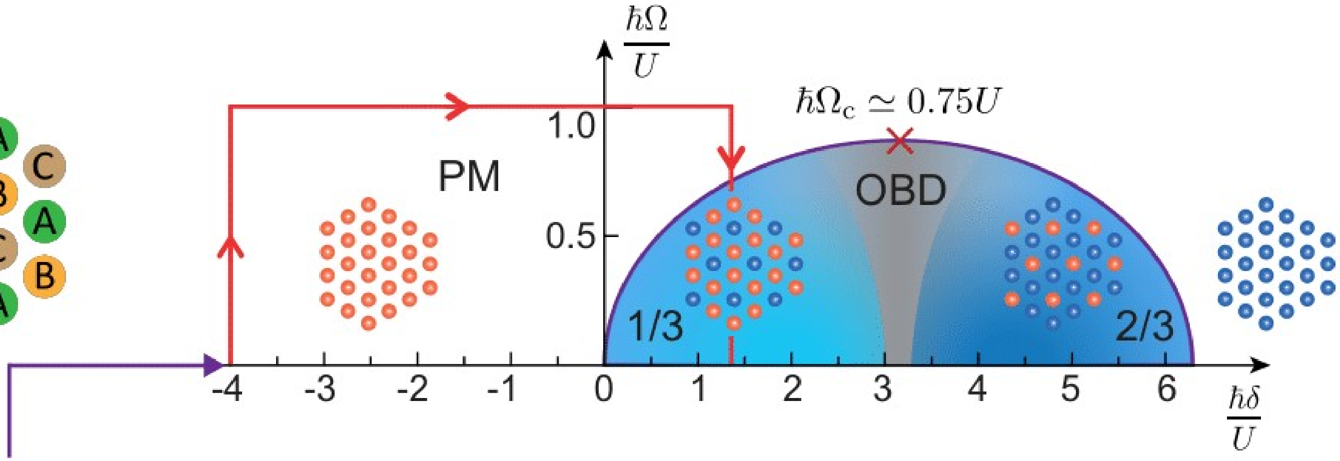
2/3 phase:

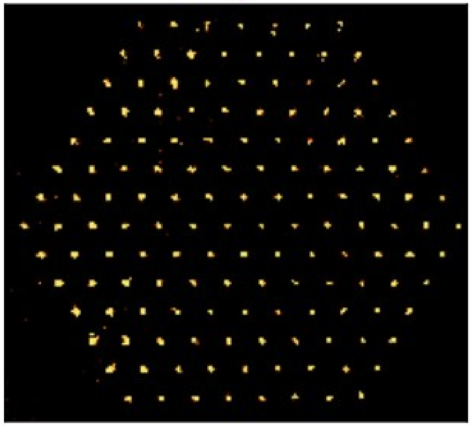


Geometrical frustration

Probing the 1/3 phase

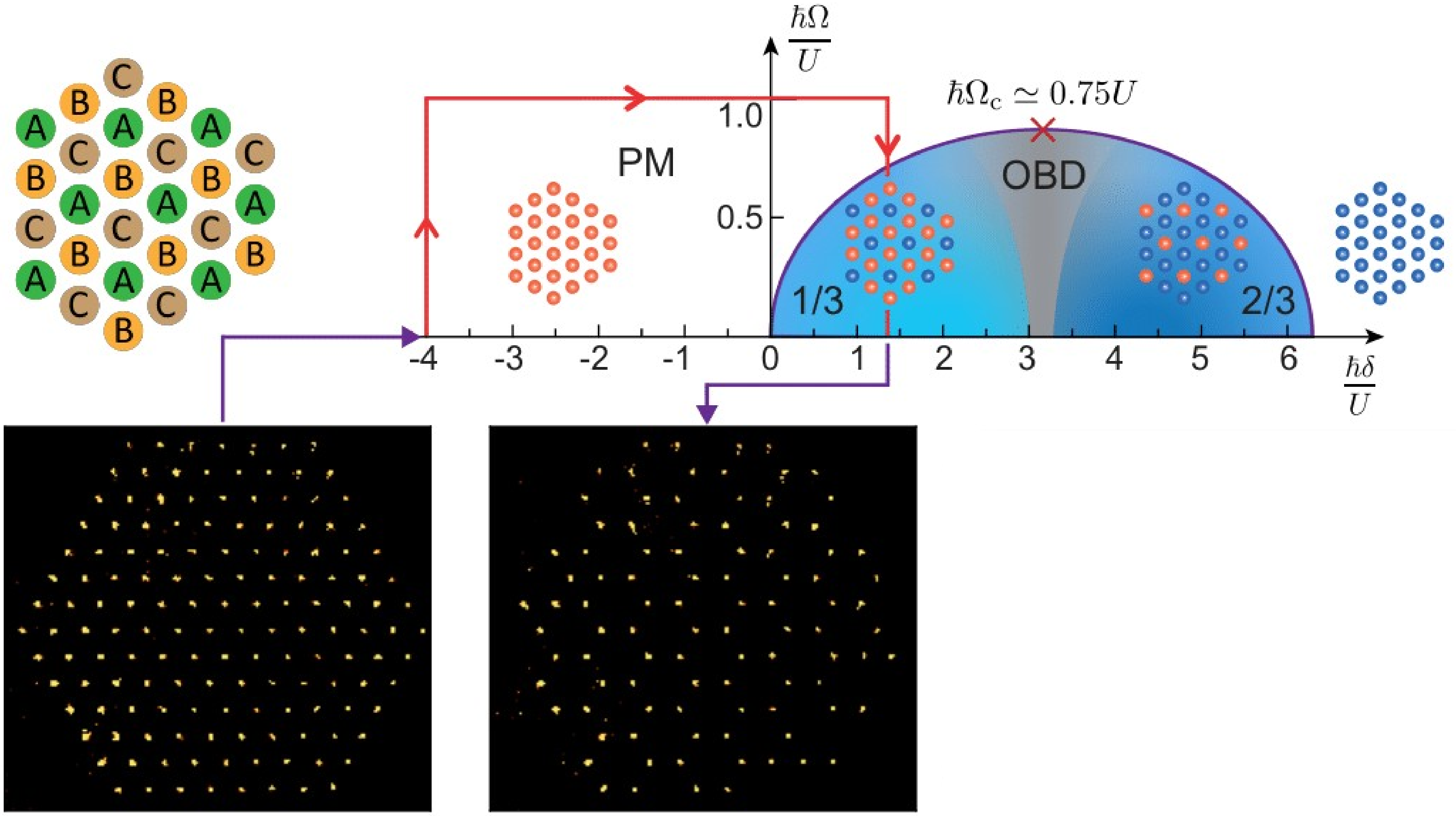






PM phase

Probing the 1/3 phase

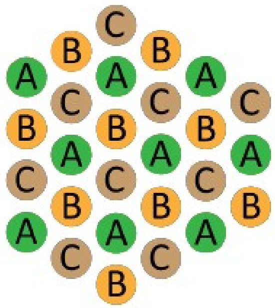


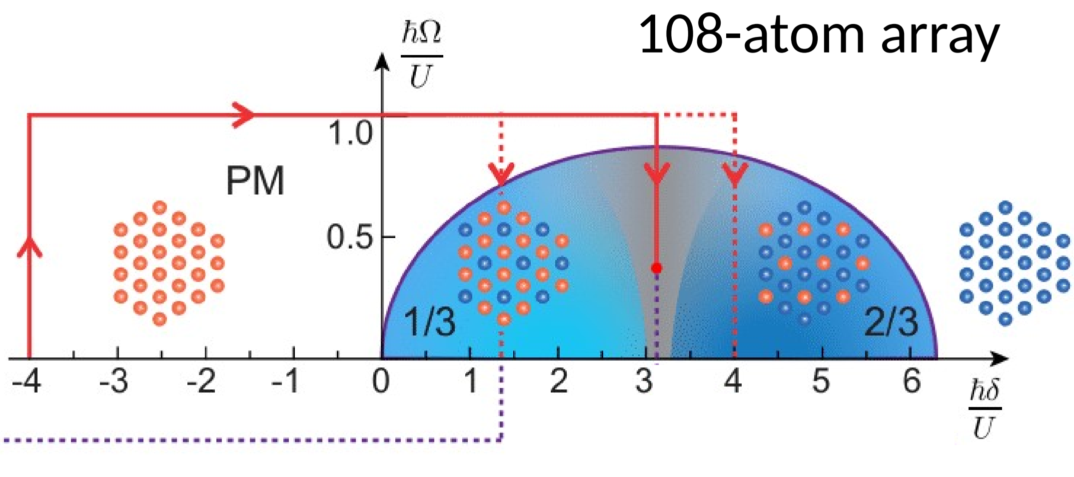
PM phase

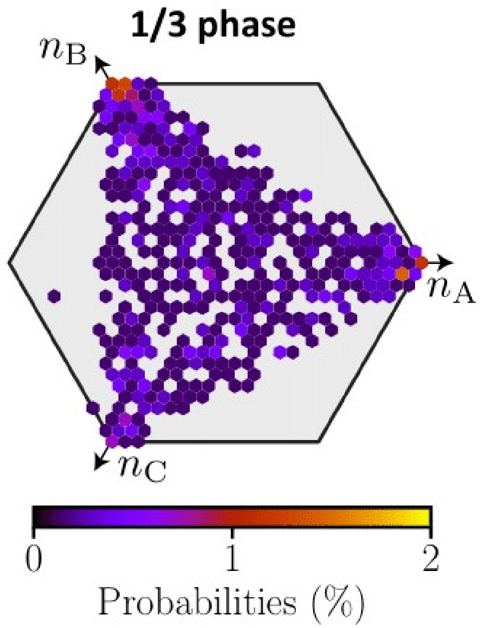
1/3 phase!

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

2D Ising anti-ferromagnet on a triangle

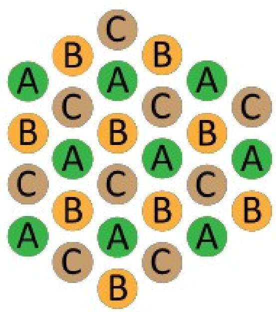




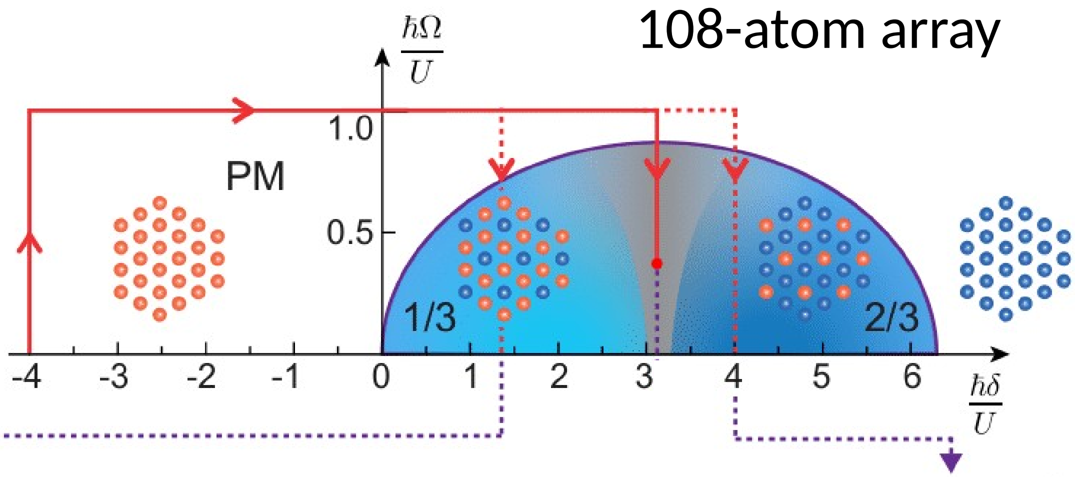


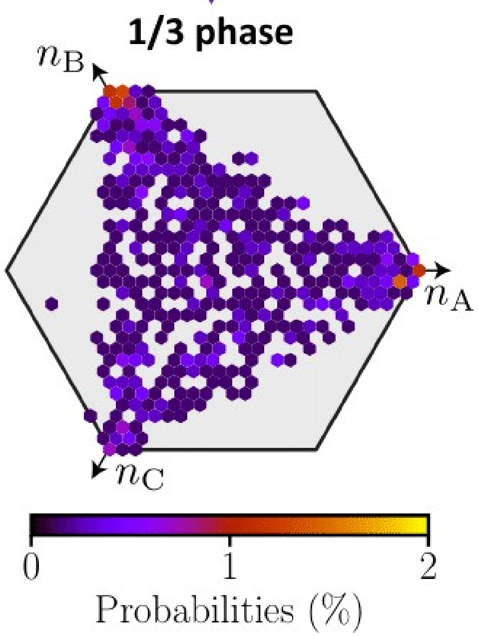
Staggered magnetisation: $$m_{\text{stag}} = n_A + n_B\, e^{i\frac{2\pi}{3}} + n_C\, e^{i\frac{4\pi}{3}}$$

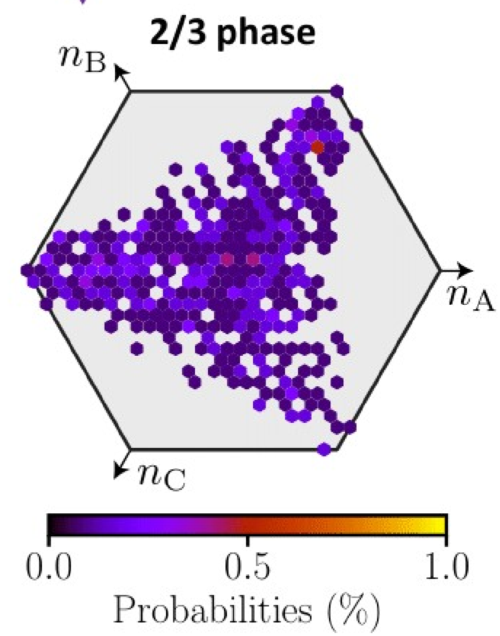
2D Ising anti-ferromagnet on a triangle



108-atom array







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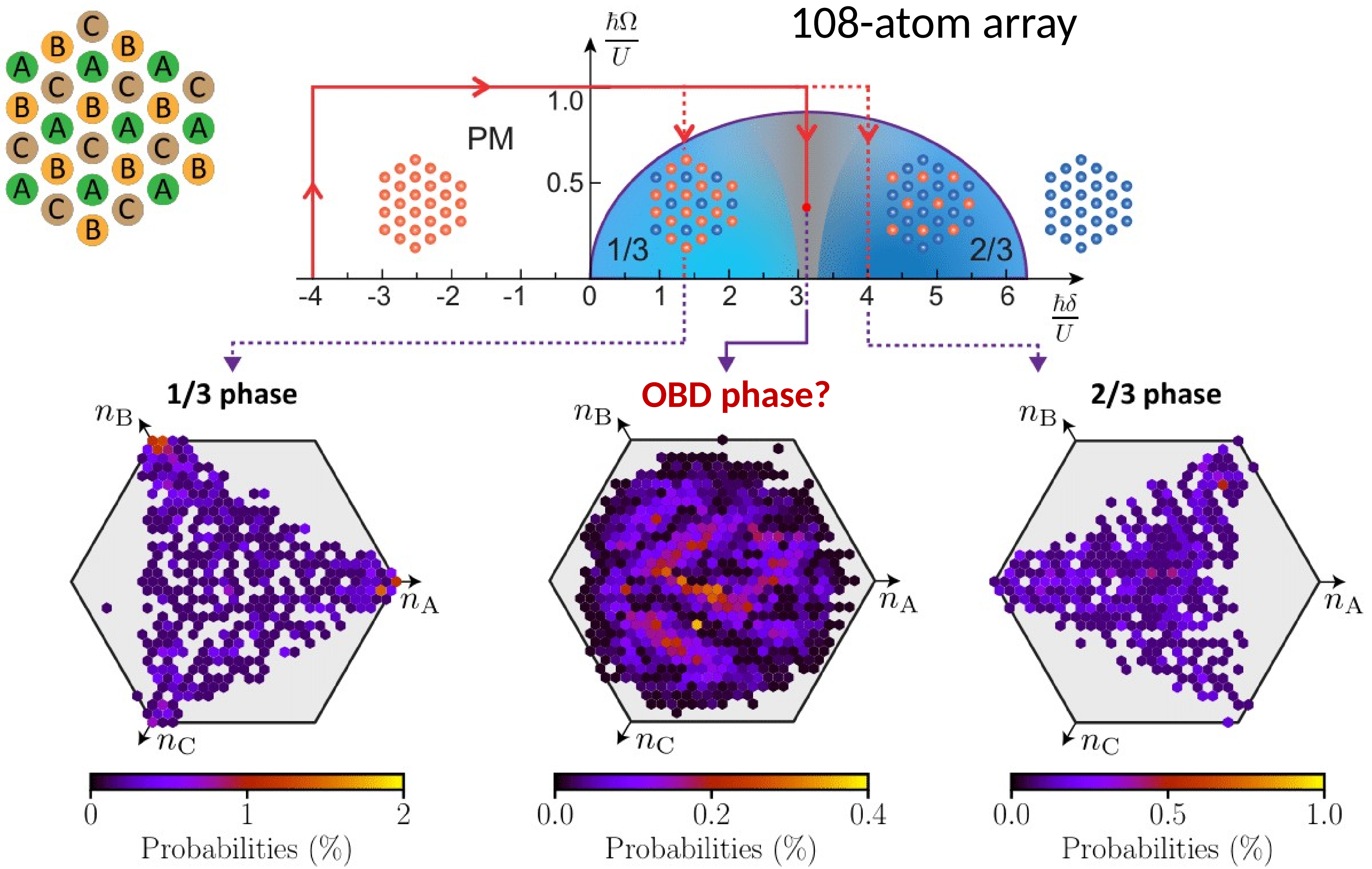
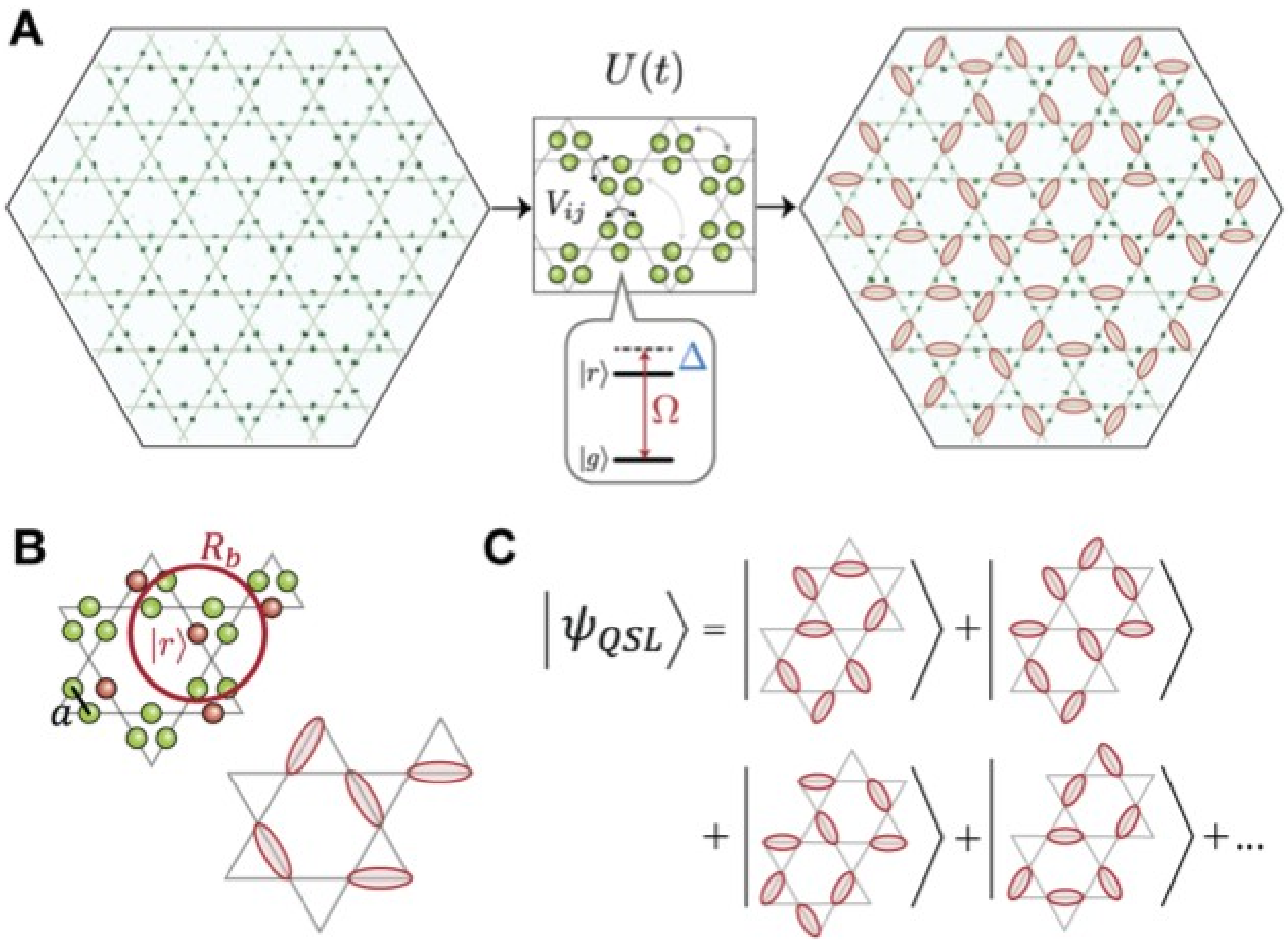
2D Ising anti-ferromagnet on a triangle



Staggered magnetisation: $m_{\text{stag}} = n_A + n_B\, e^{i\frac{2\pi}{3}} + n_C\, e^{i\frac{4\pi}{3}}$

2D Ising anti-ferromagnet on a ruby lattice: spin liquid?

Semeghini, Science **374**, 1242 (2021)



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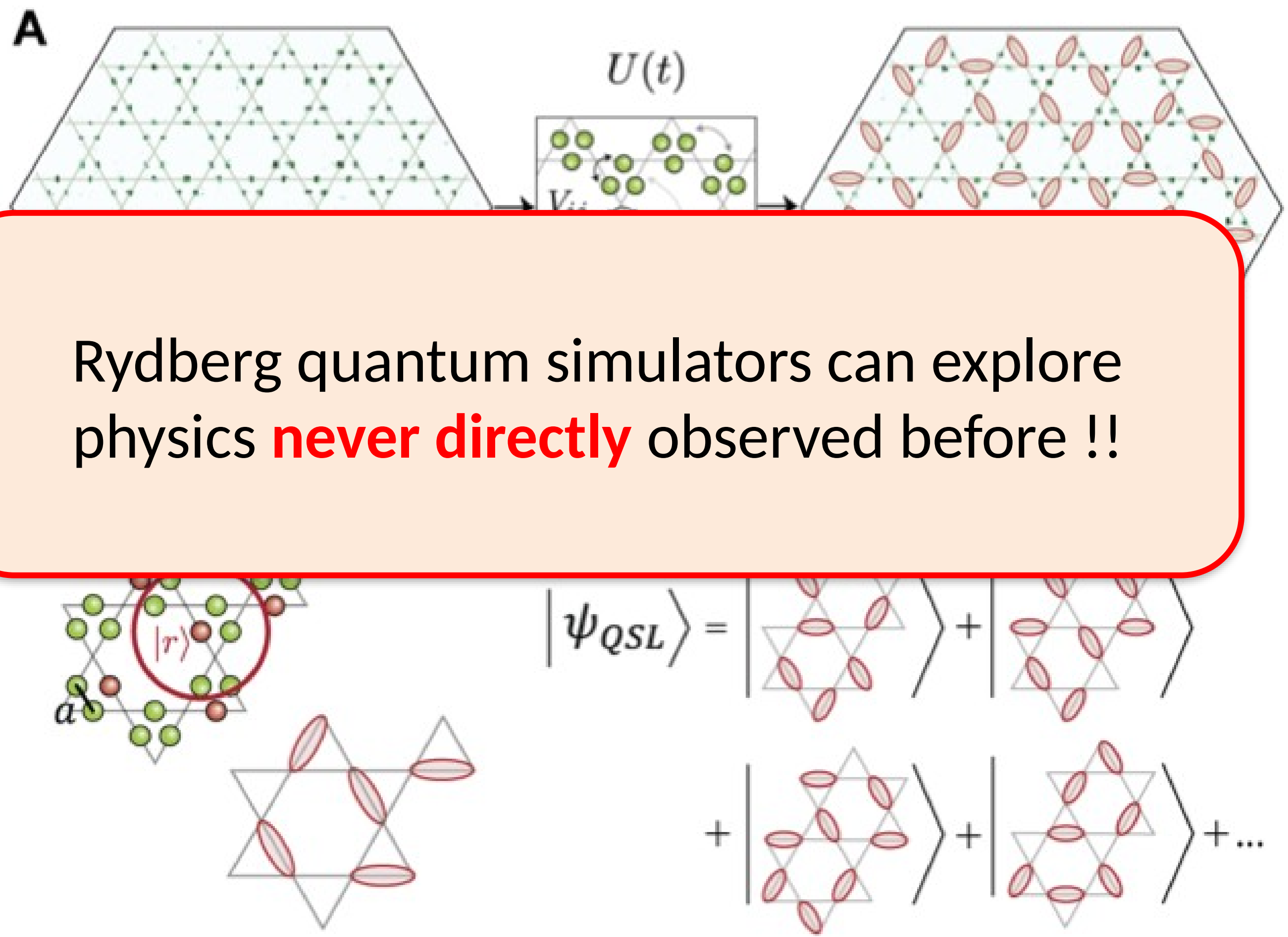
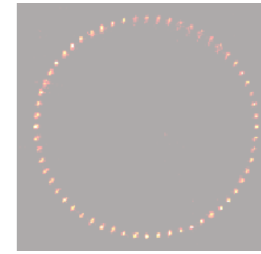


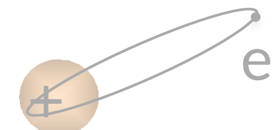
Rydberg quantum simulators can explore physics **never directly** observed before !!

Outline

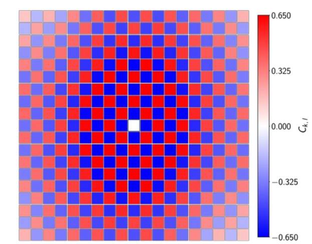
1. **Arrays of individual atoms**



2. **Rydberg atoms and their interactions**



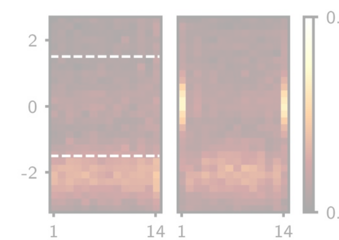
3. **Examples of quantum simulations**



   A. Exploration of phase diagrams

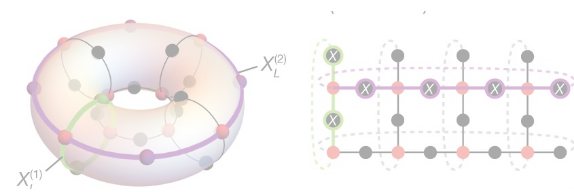
   B. Out-of-Equilibrium dynamics

   C. Ground state preparation & squeezing

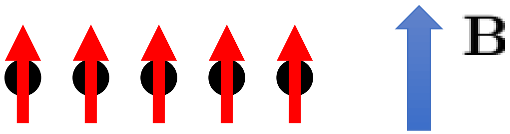


   D. Synthetic Topological matter

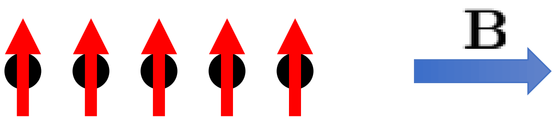
4. **Digital quantum computing**



Quench in Ising Hamiltonian

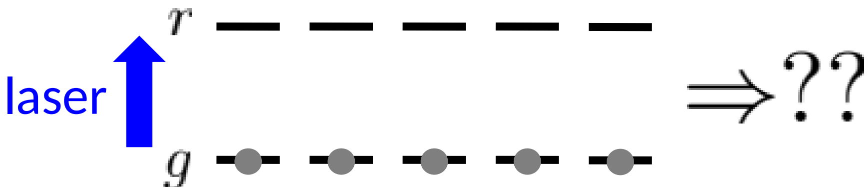


Quench in Ising Hamiltonian

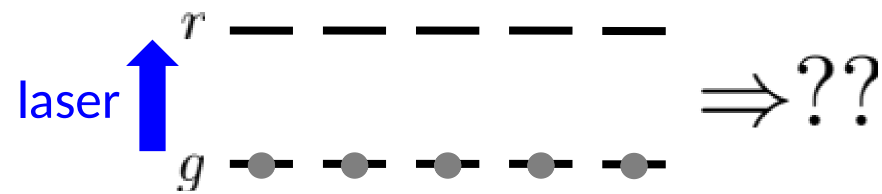


$\Rightarrow ??$

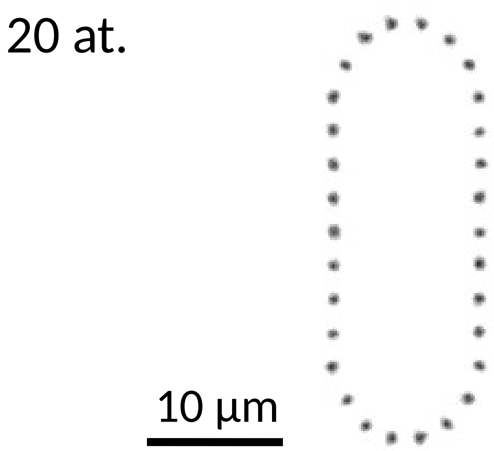
Quench in Ising Hamiltonian



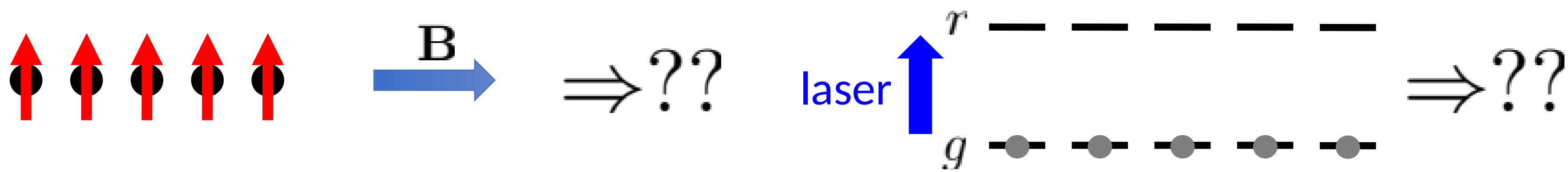
Quench in Ising Hamiltonian



1D with periodic boundaries

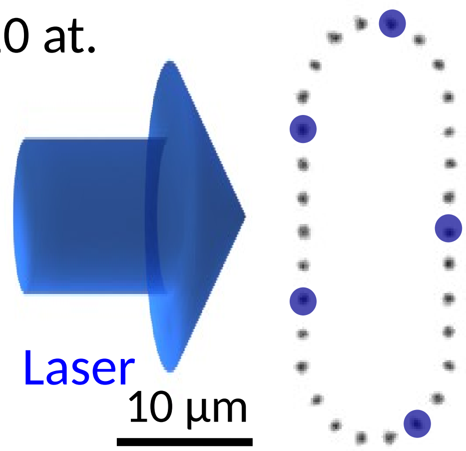


Quench in Ising Hamiltonian

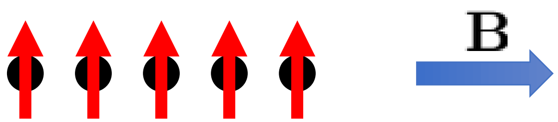


1D with periodic boundaries

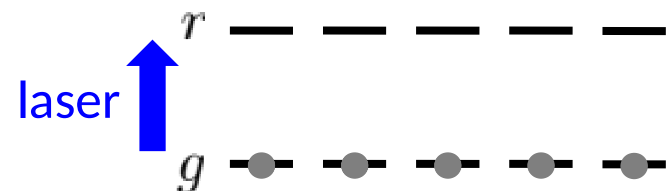
20 at.



Quench in Ising Hamiltonian



$\Rightarrow ??$



$\Rightarrow ??$

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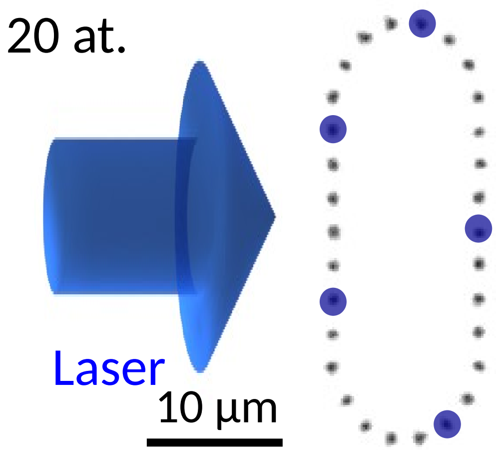
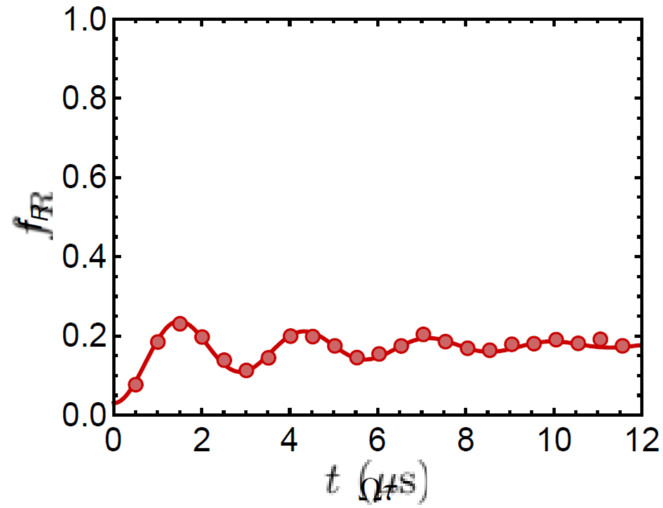
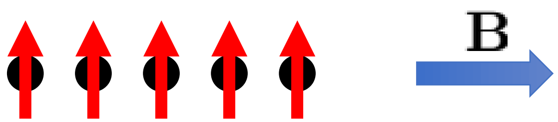


"Magnetization"

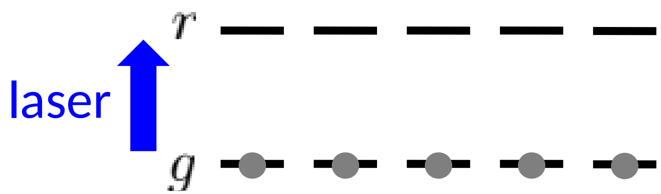
$$f_r = \frac{\langle N_r \rangle}{N}$$



Quench in Ising Hamiltonian

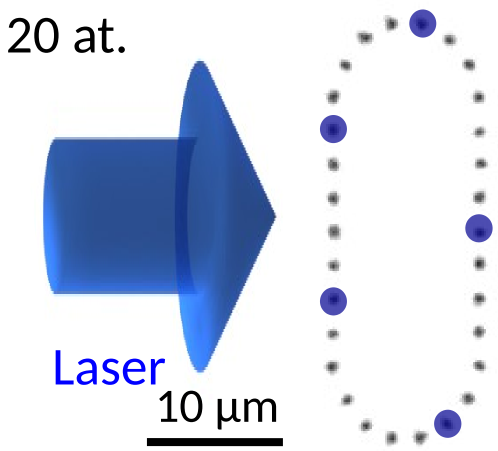


$\Rightarrow ??$



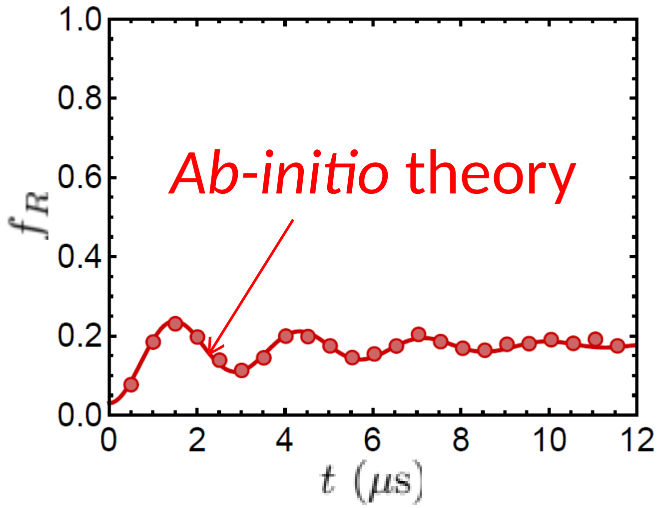
$\Rightarrow ??$

1D with periodic boundaries

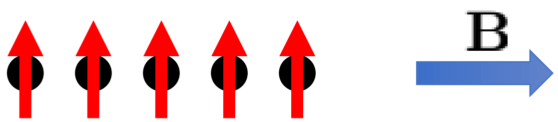


"Magnetization"

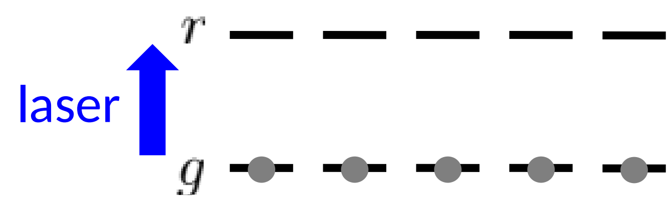
$$f_{\rm r} = \frac{\langle N_{\rm r} \rangle}{N}$$



Quench in Ising Hamiltonian

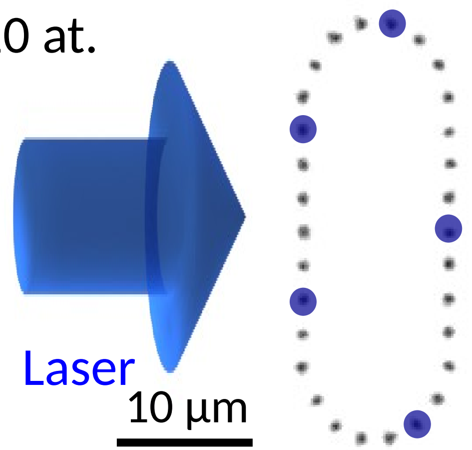


$\Rightarrow ??$



$\Rightarrow ??$

1D with periodic boundaries



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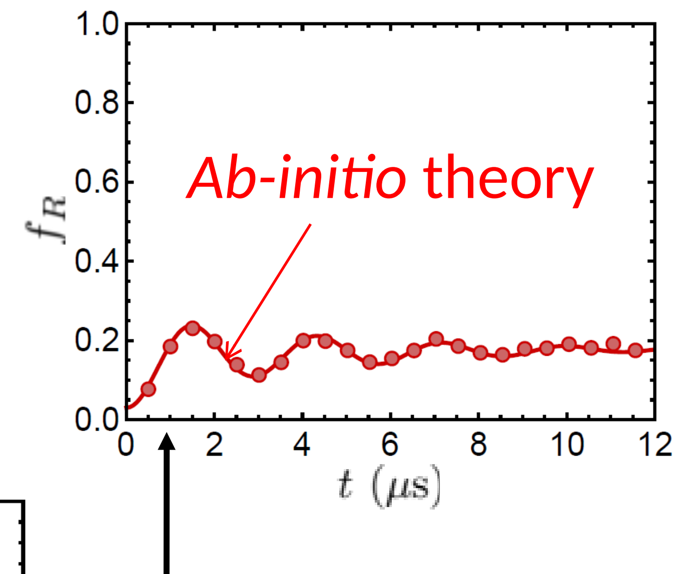
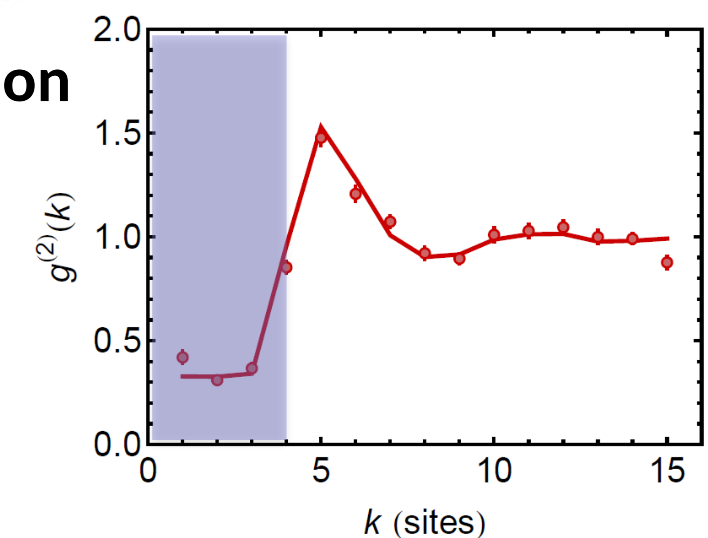
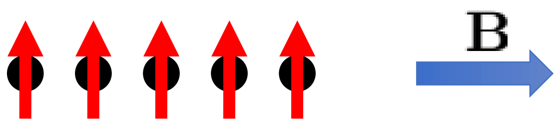


Spin-spin correlation

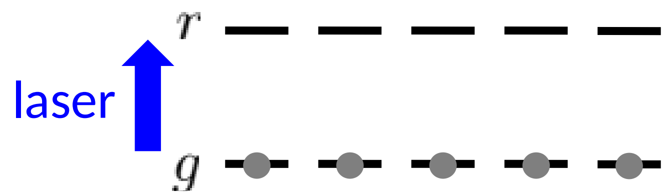
$$\sim \langle n_j n_{j+k} \rangle$$



Quench in Ising Hamiltonian



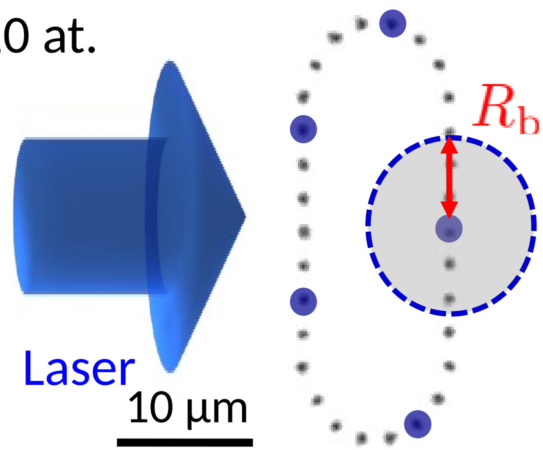
$\Rightarrow ??$



$\Rightarrow ??$

1D with periodic boundaries

20 at.



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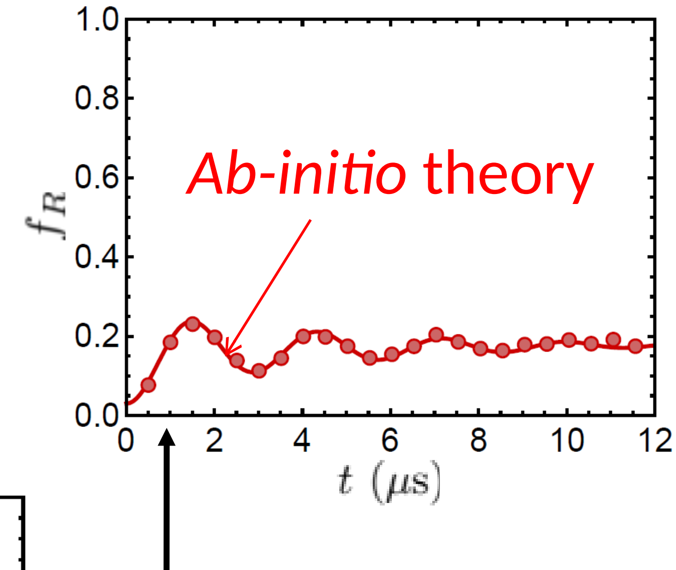
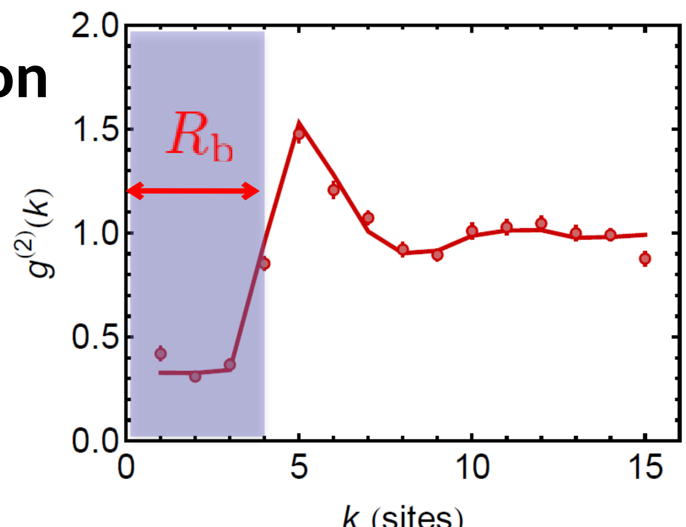


Spin-spin correlation

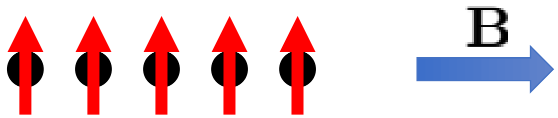


$$\sim \langle n_j n_{j+k} \rangle$$

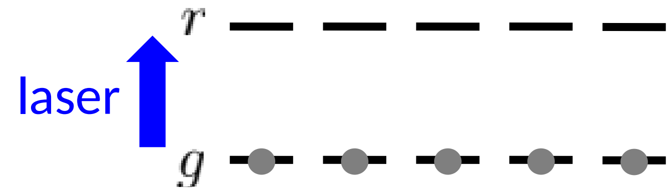
1 Rydberg atom
= hard sphere R_b

Schauss, Nature 2012
Lesanovsky, PRA 2012
Petrosyan, PRA 2013

Quench in Ising Hamiltonian

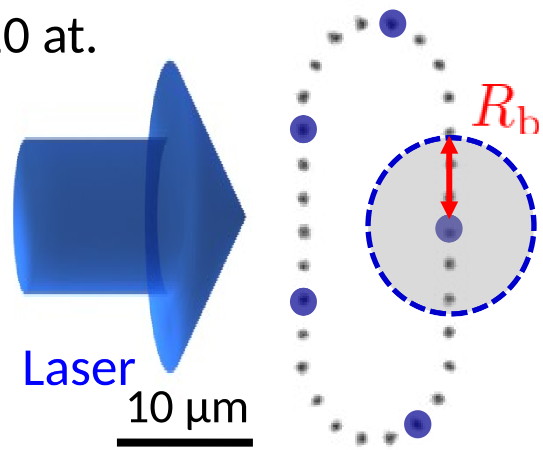


$\Rightarrow ??$



$\Rightarrow ??$

1D with periodic boundaries



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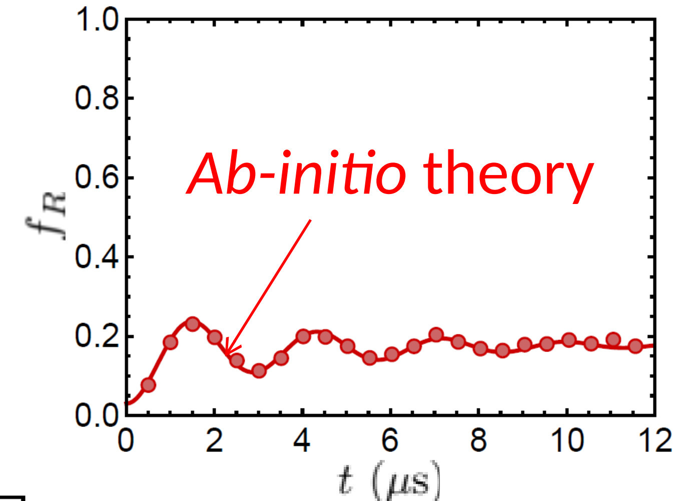

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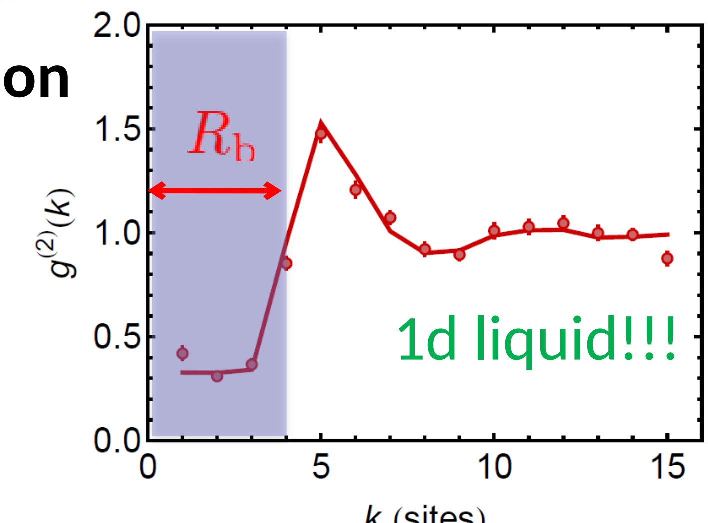
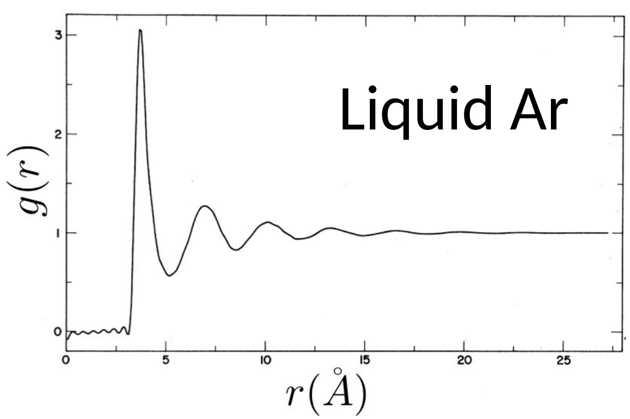
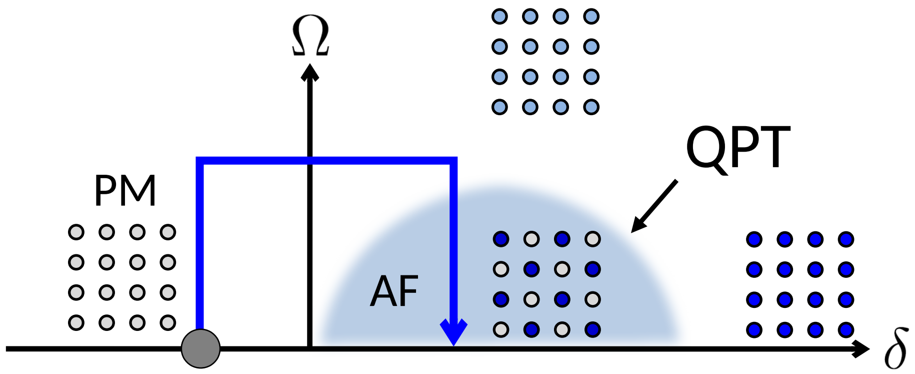




Schauss, Nature 2012
Lesanovsky, PRA 2012
Petrosyan, PRA 2013

Studying the quantum phase transition



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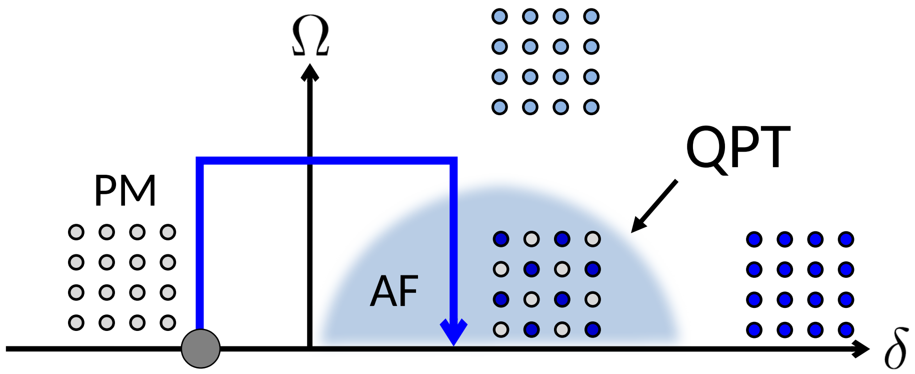
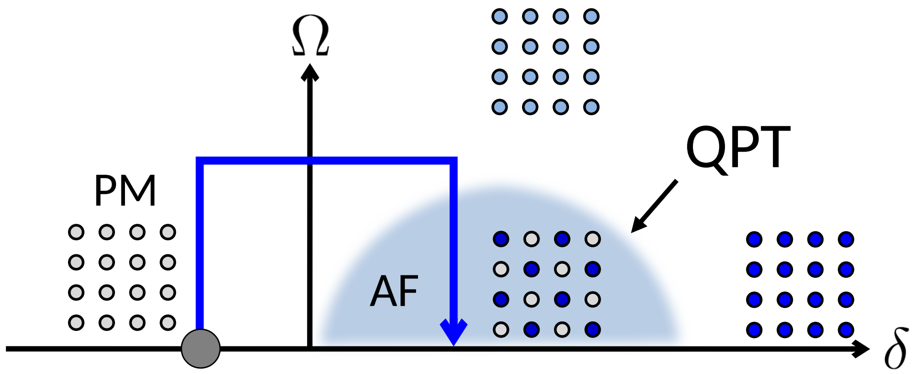


Adiabaticity criteria:

$$H(t) = (1-\lambda(t))H_0 + \lambda(t)H_{\mathrm{MB}}$$

$$|\langle\psi_1(t)|\frac{dH}{dt}|\psi_0(t)\rangle| \ll \frac{\Delta E(t)^2}{\hbar}$$

Studying the quantum phase transition



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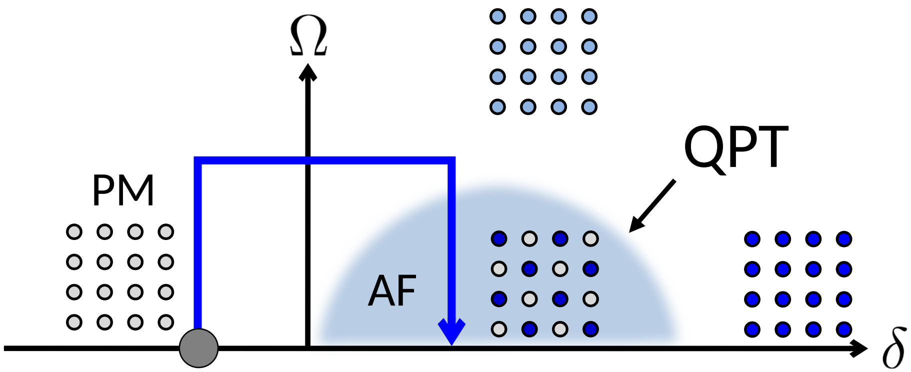
But...gaps close at the QPT!!

Studying the quantum phase transition



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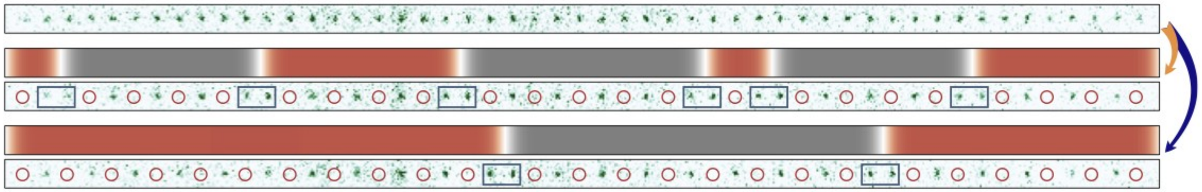
But...gaps close at the QPT!!

Sweeping too fast = create defects

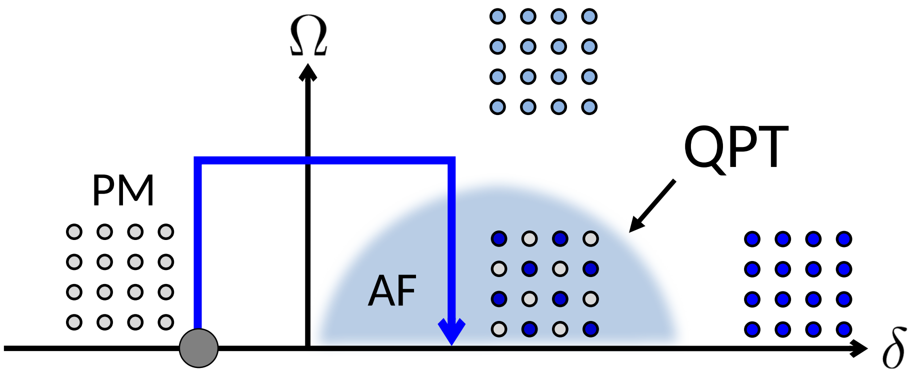
1D: Keesling, Nature (2019), 2D: arXiv.2012.12281

$R_b \sim a$

51 atoms



Studying the quantum phase transition



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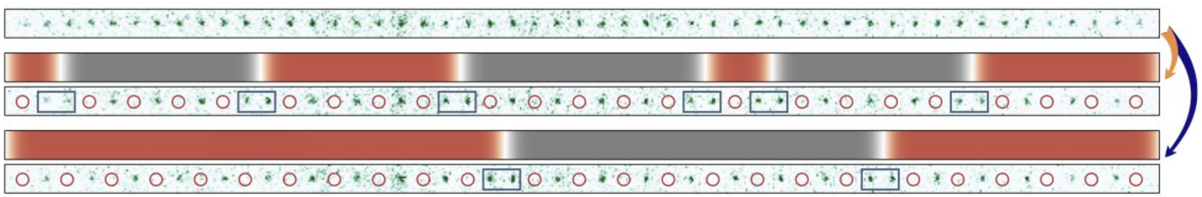
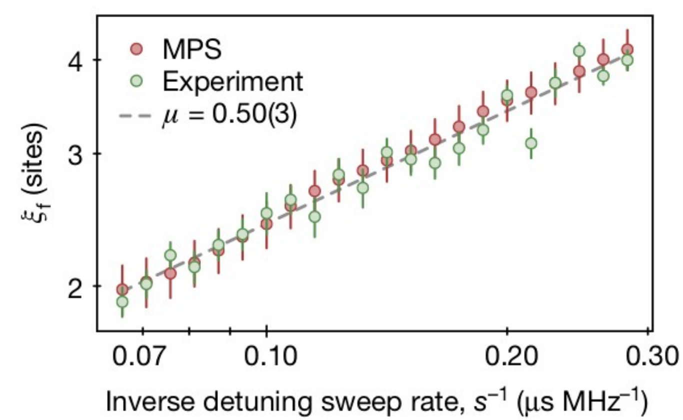
But...gaps close at the QPT!!

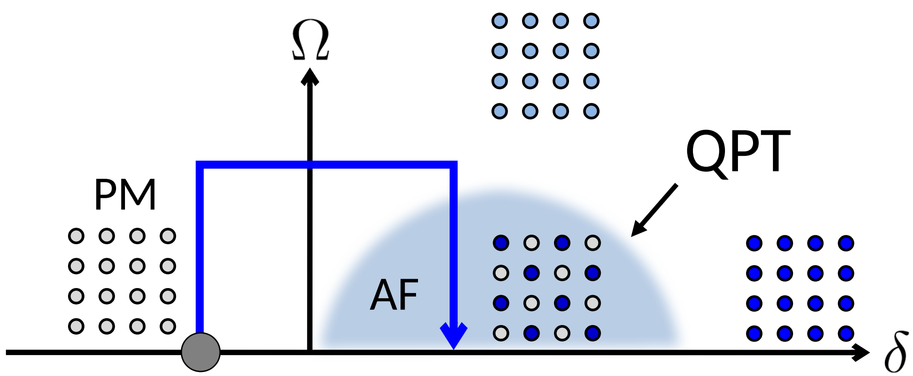
Sweeping too fast $\Rightarrow$ create defects 1D: Keesling, Nature (2019), 2D: arXiv.2012.12281

$R_b \sim a$ 51 atoms





Studying the quantum phase transition



Adiabaticity criteria:

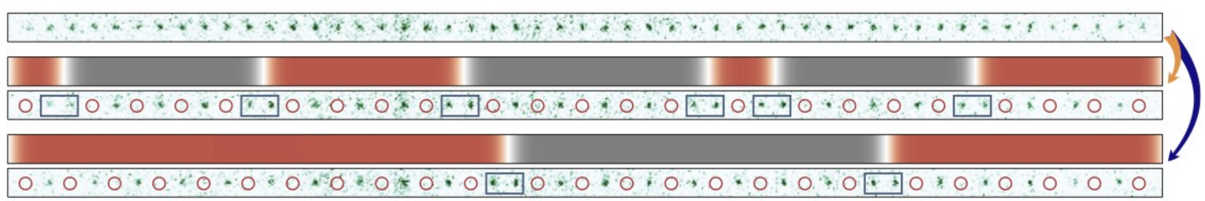
$$H(t) = (1-\lambda(t))H_0 + \lambda(t)H_{\mathrm{MB}}$$

$$|\langle\psi_1(t)|\frac{dH}{dt}|\psi_0(t)\rangle| \ll \frac{\Delta E(t)^2}{\hbar}$$

But...gaps close at the QPT!!

Sweeping too fast ⇒ create defects   1D: Keesling, Nature (2019), 2D: arXiv.2012.12281

$R_b \sim a$ 51 atoms

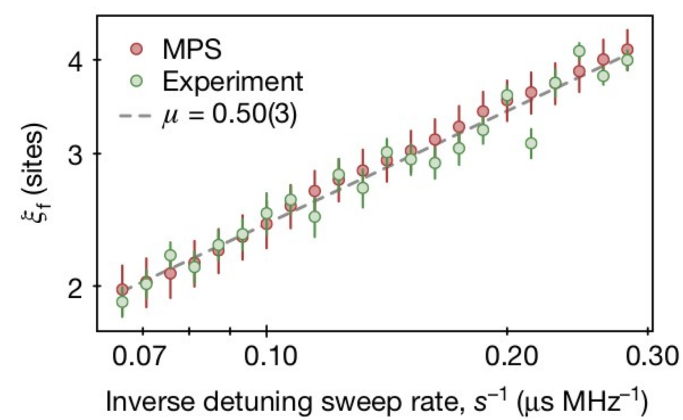


Kibble-Zurek mechanism:

statistics of defects ⇒ critical exponent

ν_{1D} = 0.50(3) (ν_{MF} = 1/3)

$\nu_{2D,square}$ = 0.62(4) (ν_{MF} = 1/2)



Non-equilibrium: thermalization of closed many-body systems

Question: do closed systems always reach equilibrium?

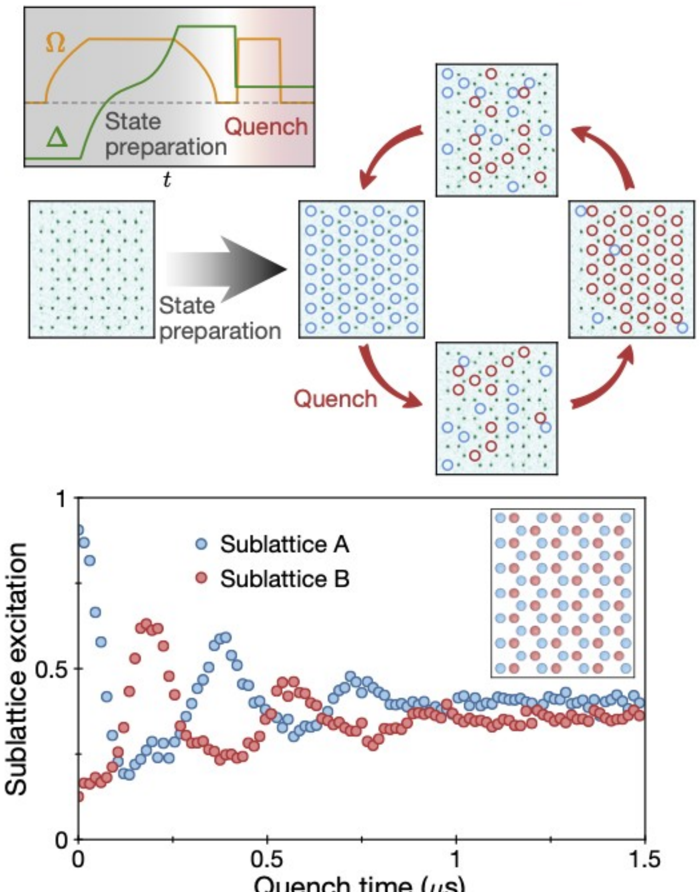
Answer: it depends… ETH, many-body localization

Non-equilibrium: thermalization of closed many-body systems

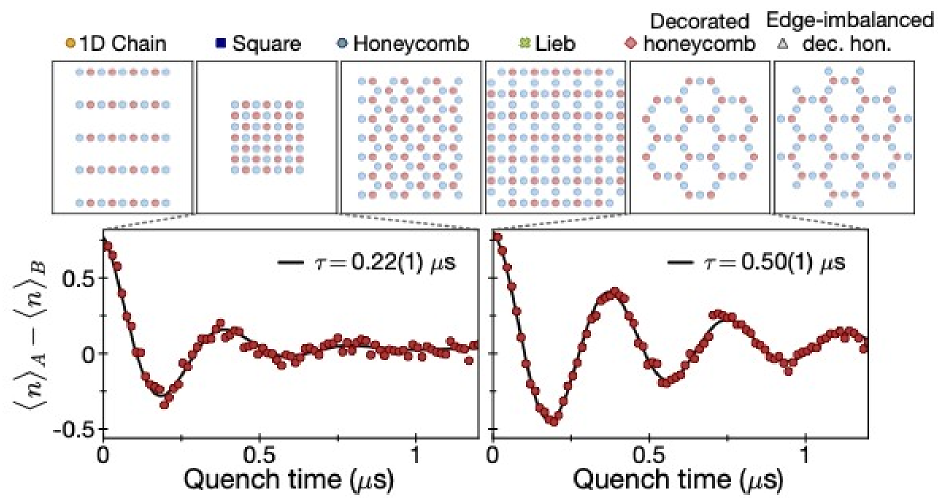
Question: do closed systems always reach equilibrium?

Answer: it depends… ETH, many-body localization

Quantum scars in 2D (**1D:** Lukin Nature 2019)



Scars depends on geometry

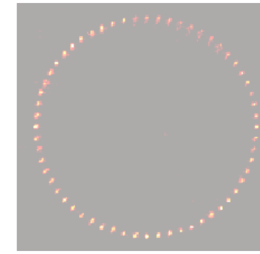


Lukin, Science 2021

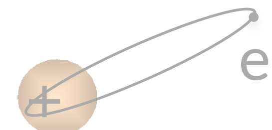
Questions?

Outline

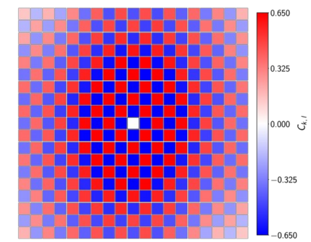
1. **Arrays of individual atoms**



2. **Rydberg atoms and their interactions**



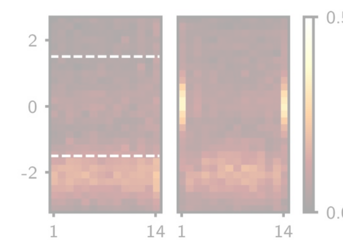
3. **Examples of quantum simulations**



   A. Exploration of phase diagrams

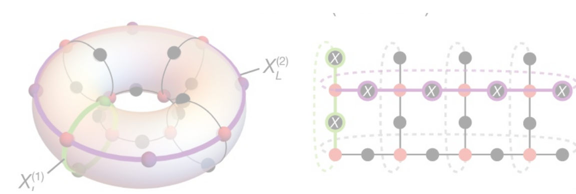
   B. Out-of-Equilibrium dynamics

   C. Ground state preparation & squeezing



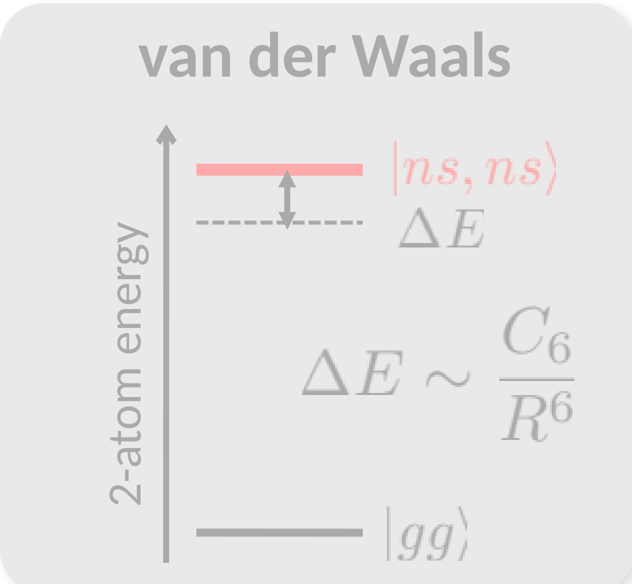
   D. Synthetic Topological matter

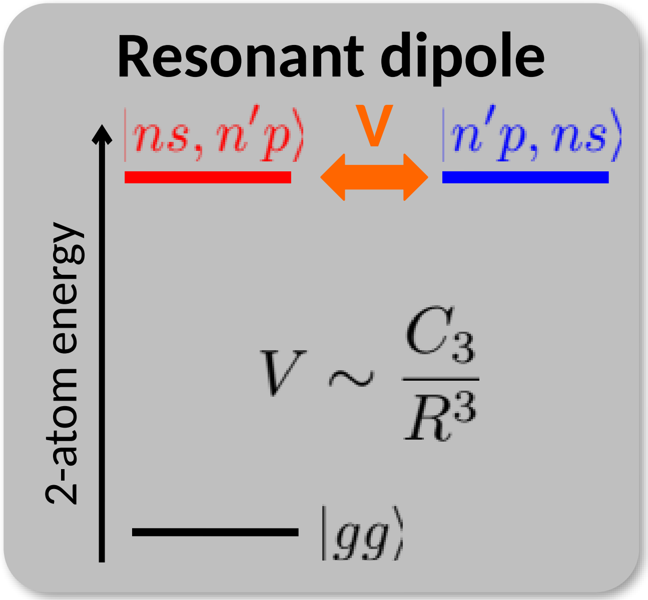
4. **Digital quantum computing**



Interactions between Rydberg atoms and spin models

Browaeys & Lahaye, Nat.Phys. (2020)





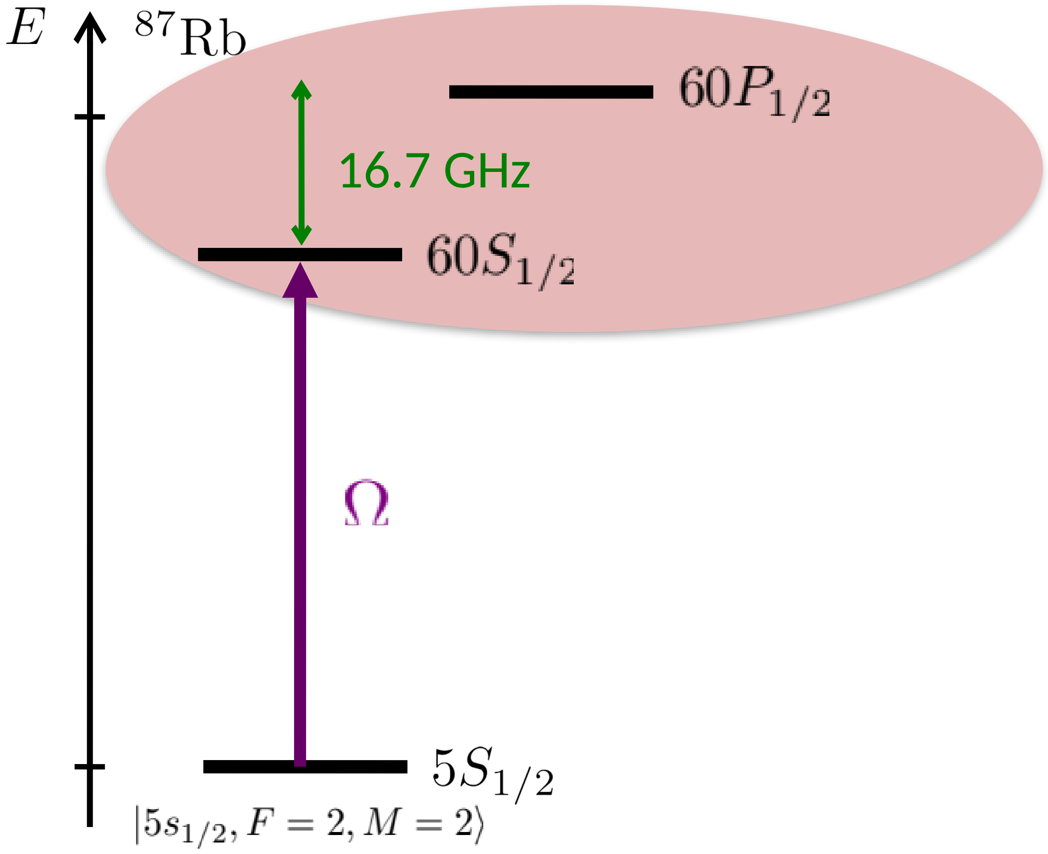
Quantum Ising

$$\hat{H} = \sum_{i \neq j} J_{ij} \hat{\sigma}_z^{(i)} \hat{\sigma}_z^{(j)}$$

XY model

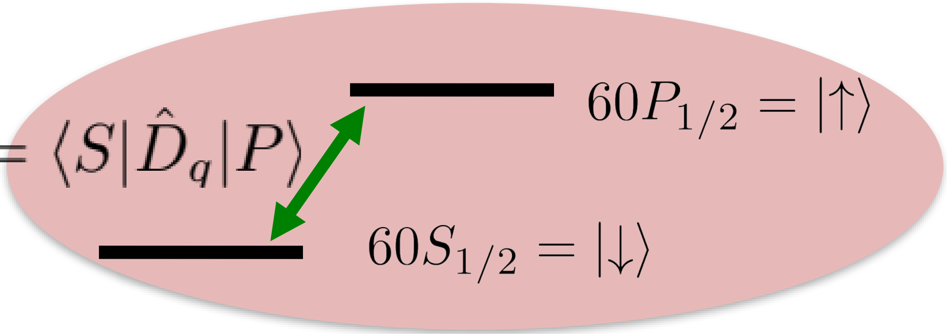
$$\hat{H} = \sum_{i \neq j} J_{ij} \left(\hat{\sigma}_i^+ \hat{\sigma}_j^- + \hat{\sigma}_i^- \hat{\sigma}_j^+ \right)$$

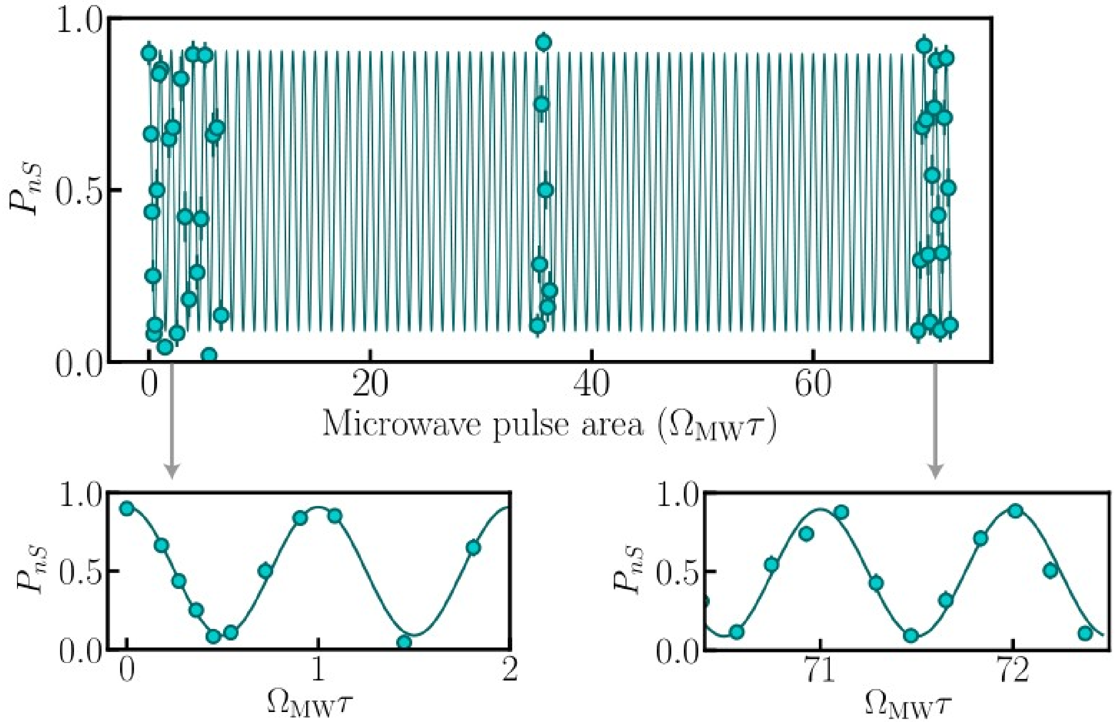
Resonant dipole-dipole interaction between Rydberg atoms



Resonant dipole-dipole interaction between Rydberg atoms

$$d = \langle S|\hat{D}_q|P\rangle$$





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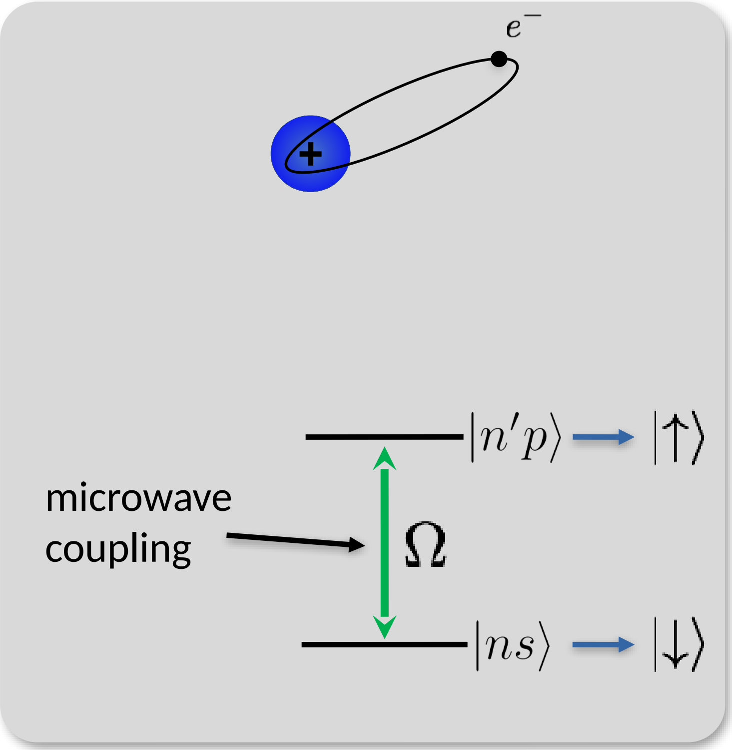
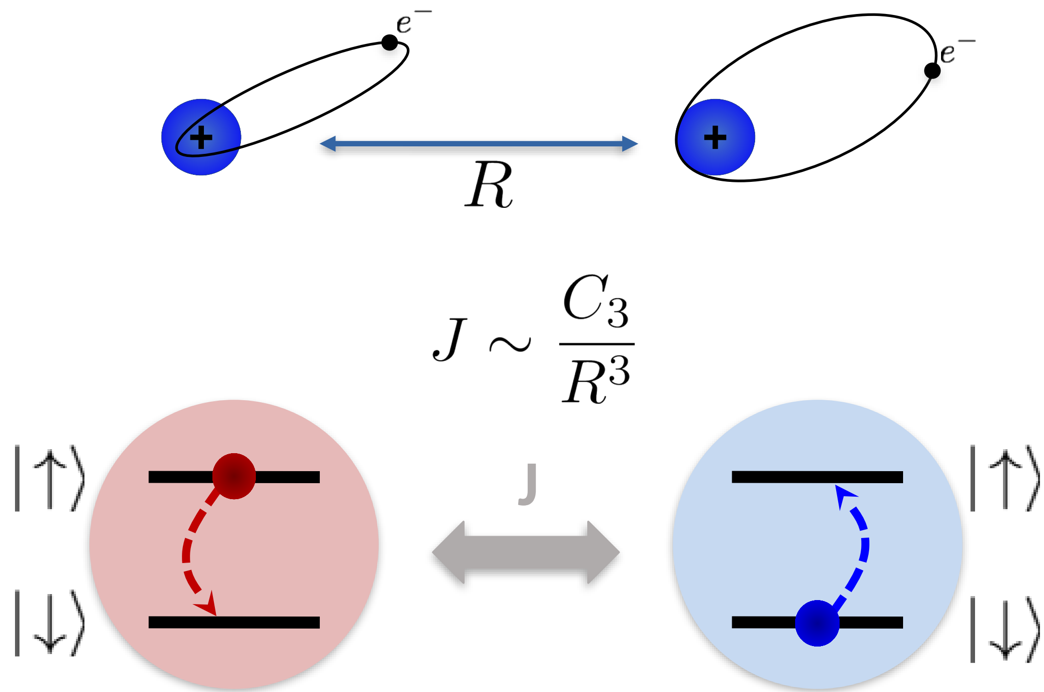
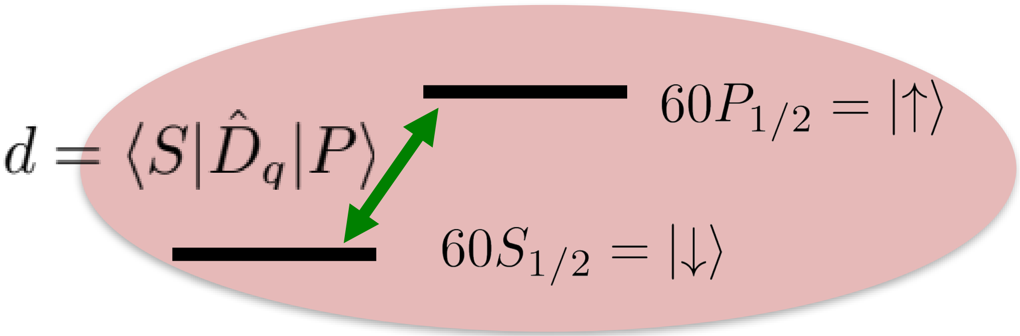


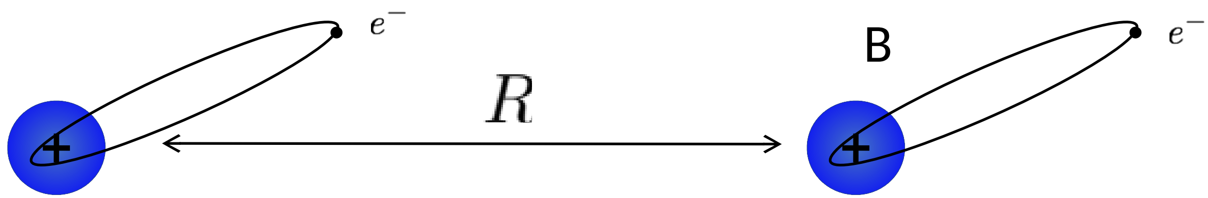


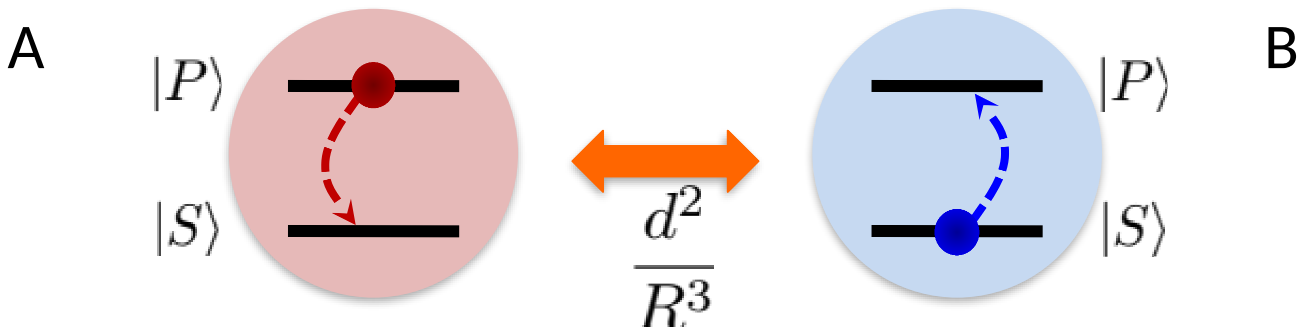
XY model:

$$H = \sum_{i \neq j} \frac{C_3}{R_{ij}^3} (\sigma_x^i \sigma_x^j + \sigma_y^i \sigma_y^j)$$

Resonant dipole-dipole interaction between Rydberg atoms







$$\hat{H} = \frac{d^2}{4\pi\epsilon_0 R^3}\left(\hat{\sigma}_A^+\hat{\sigma}_B^- + \hat{\sigma}_A^-\hat{\sigma}_B^+\right)$$

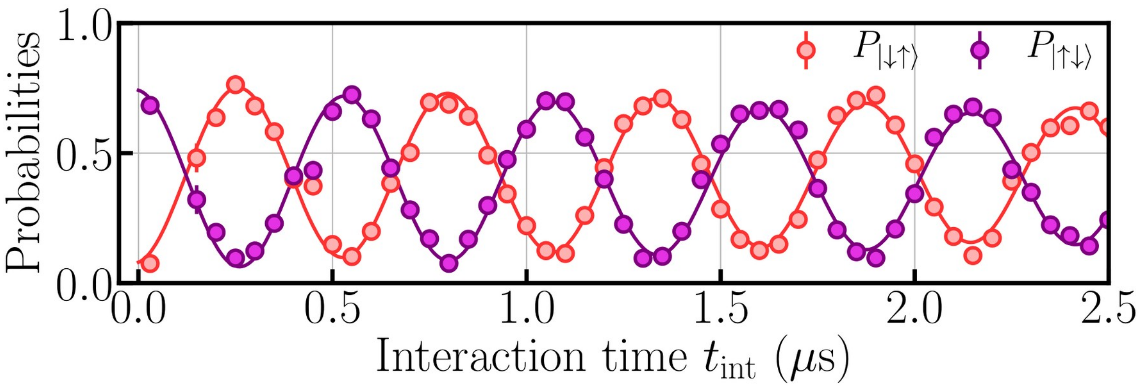
"exchange" of *P* excitation (XY model)

Resonant dipole-dipole interaction between Rydberg atoms

Prepare $|PS\rangle$ using microwaves + addressing beam

R = 30 µm

Frequency: $\frac{2C_3}{R^3}$



Barredo PRL (2015)
de Léséleuc, PRL (2017)

Resonant dipole-dipole interaction between Rydberg atoms

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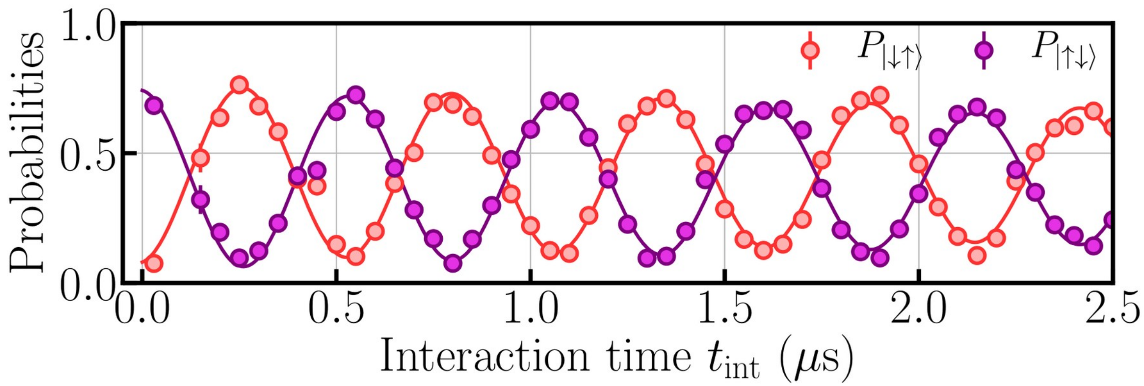
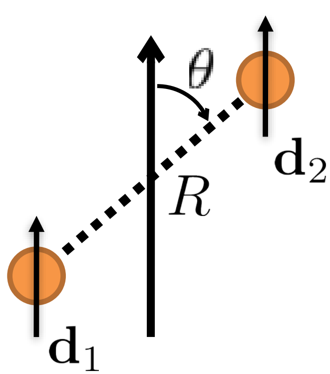
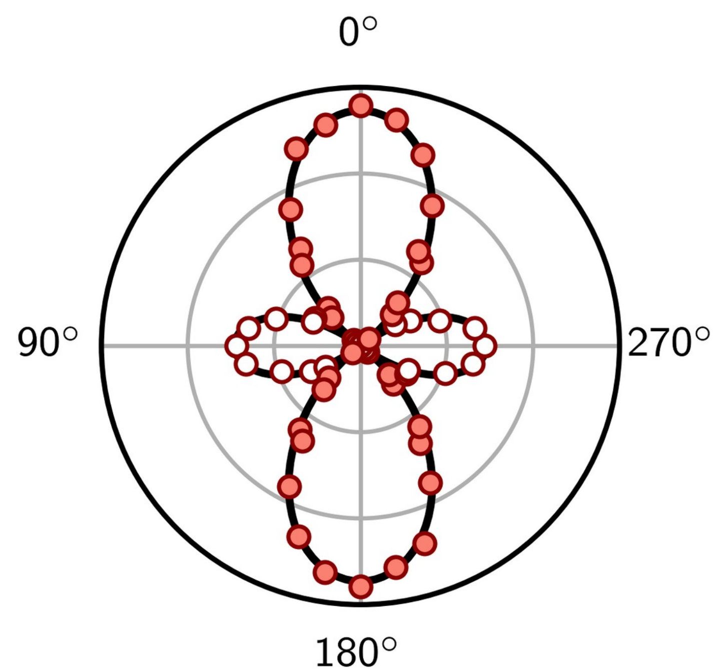


Quantization axis (B)



$$C_3(\theta) \propto 1 - 3\cos^2\theta$$



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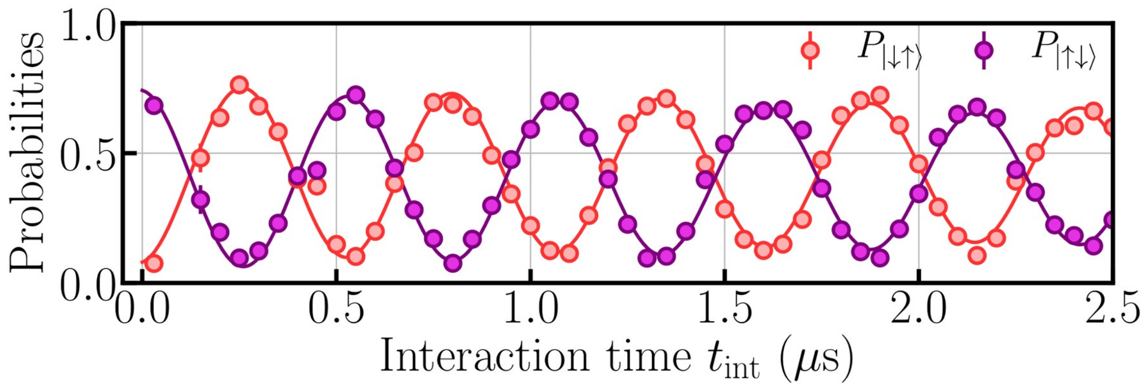
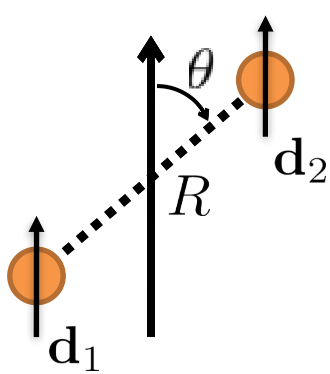


Quantization axis (B)



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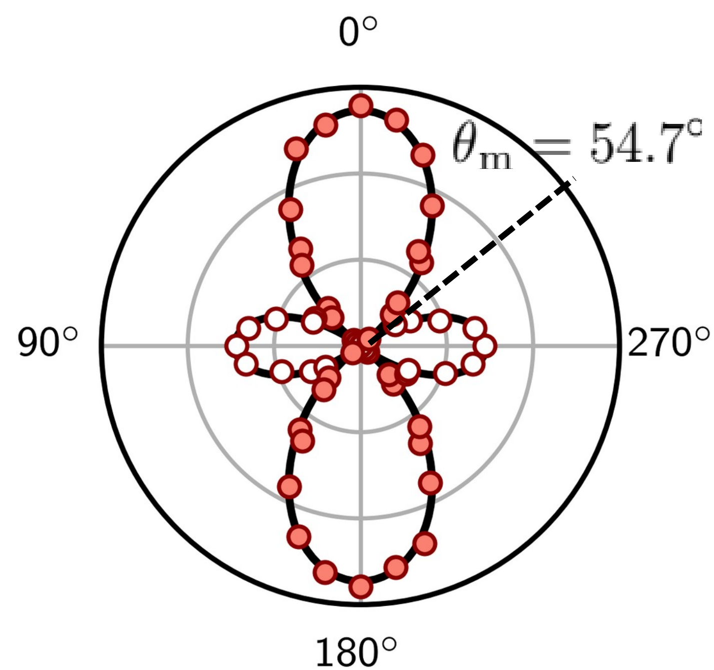

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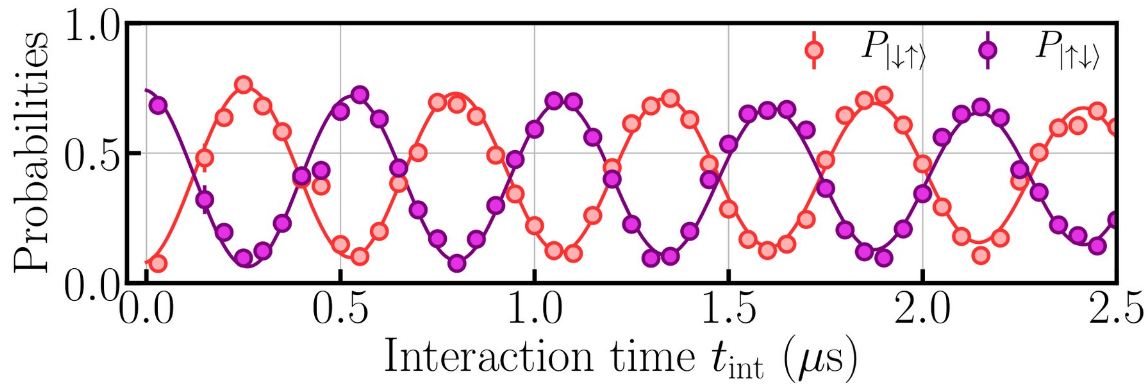
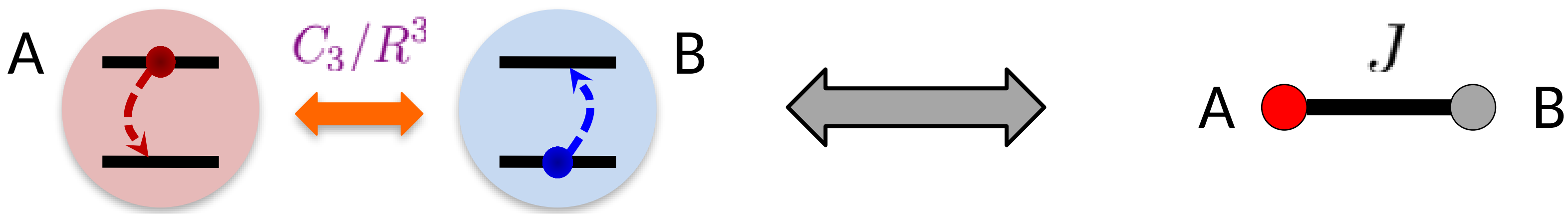




P excitation exchange

Particle hopping

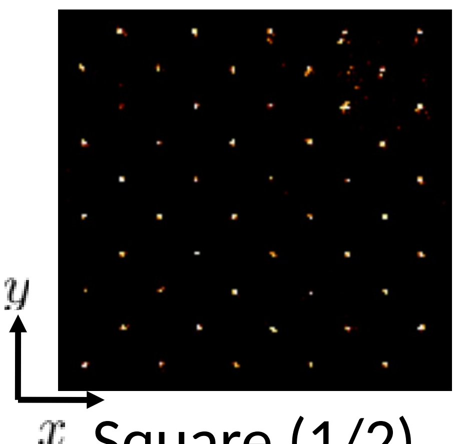
$$J|A\rangle\langle B|$$

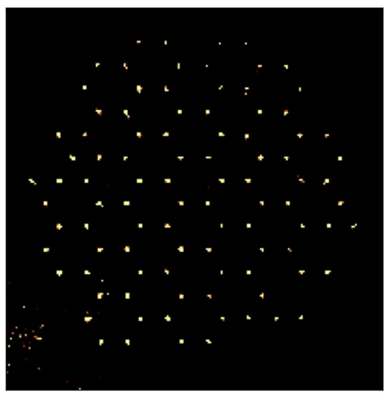
Ising vs XY model

Ising model

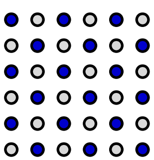
$$\hat{H} = \sum_{\langle i,j \rangle} J_{ij} \hat{\sigma}_i^x \hat{\sigma}_j^x$$

Antiferro $J_{ij} < 0$





Square (1/2) Triangle (1/3)



$$\rightarrow_x \leftarrow_x \rightarrow_x \cdots$$
$$\leftarrow_x \rightarrow_x \leftarrow_x \cdots$$
$$\rightarrow_x \leftarrow_x \rightarrow_x \cdots$$

Ground state (1/2, 1/3…) =
classical Néel configurations

Ising vs XY model

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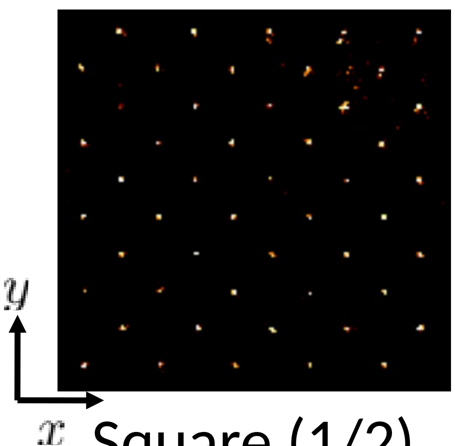
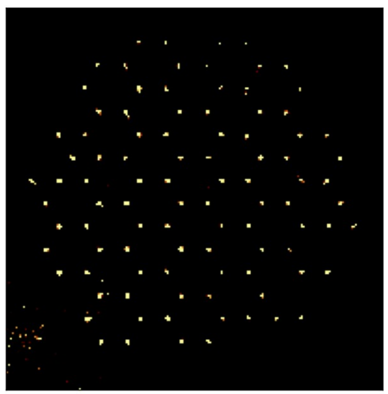
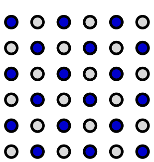


Square (1/2)



Triangle (1/3)



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Ground state (1/2, 1/3...) =
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XY model

$$\hat{H} = \sum_{\langle i,j \rangle} J_{ij} (\hat{\sigma}_i^x \hat{\sigma}_j^x + \hat{\sigma}_i^y \hat{\sigma}_j^y)$$

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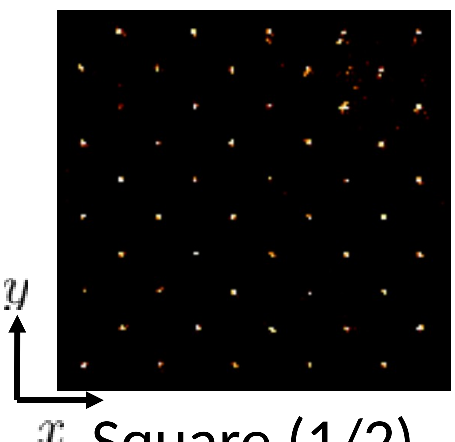
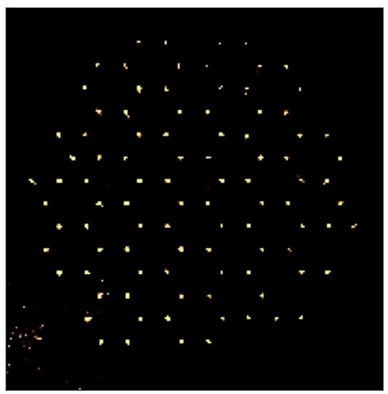
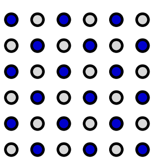


Square (1/2)



Triangle (1/3)



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XY model

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Competing order along *x* / along *y*

Ising vs XY model

Ising model

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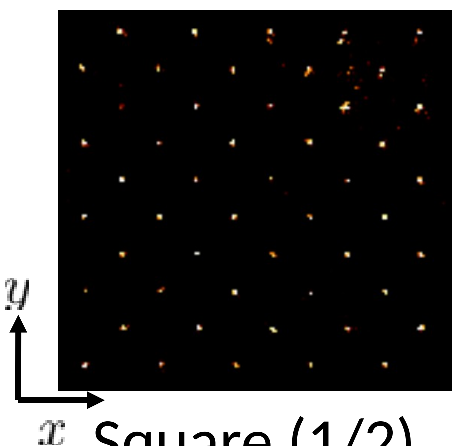
Antiferro $J_{ij} < 0$



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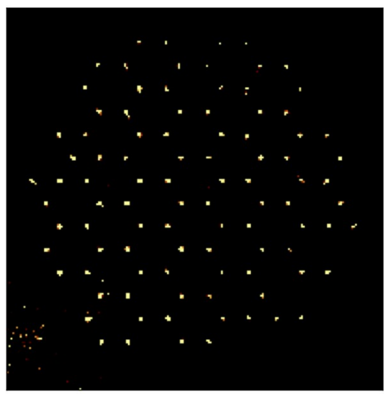

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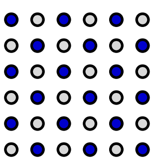

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$$= \sum_{\langle i,j \rangle} \frac{J_{ij}}{2} (\hat{\sigma}_i^+ \hat{\sigma}_j^- + \hat{\sigma}_i^- \hat{\sigma}_j^+)$$

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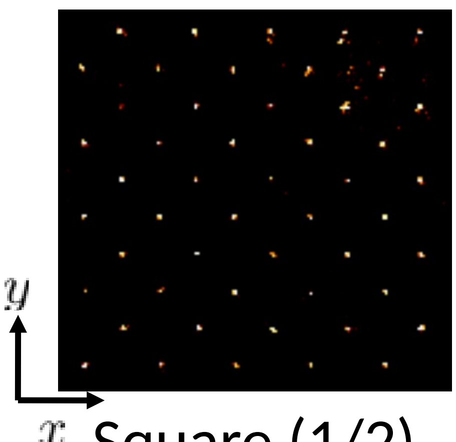

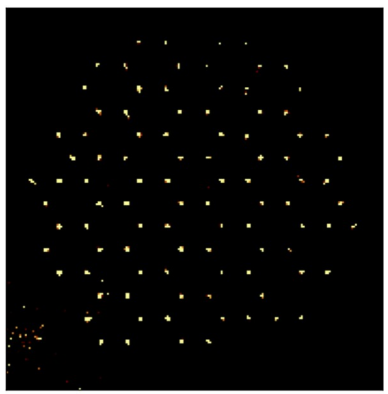

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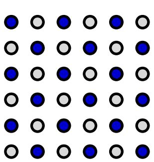

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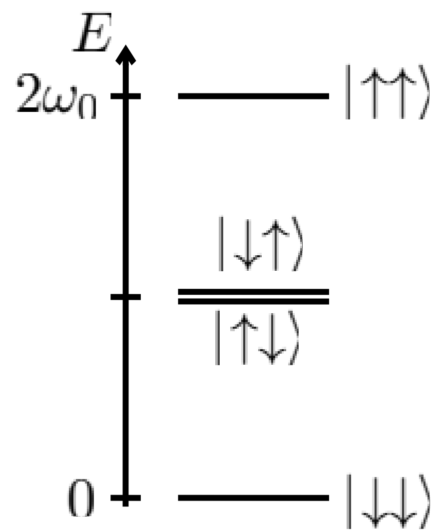

Ising vs XY model

Ising model

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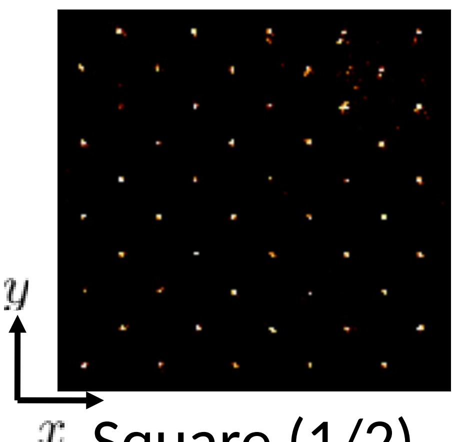
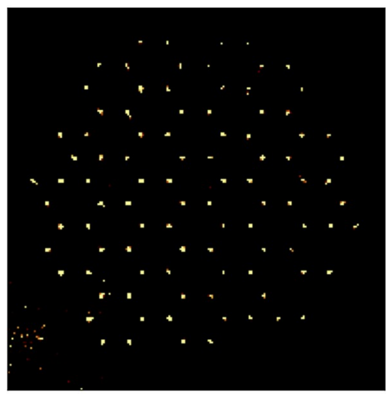
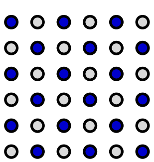


Square (1/2)



Triangle (1/3)



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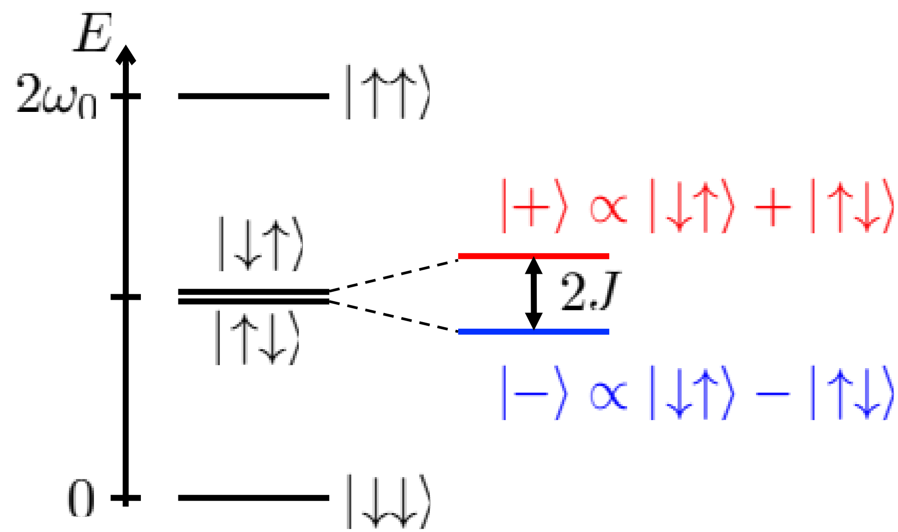

Ising vs XY model

Ising model

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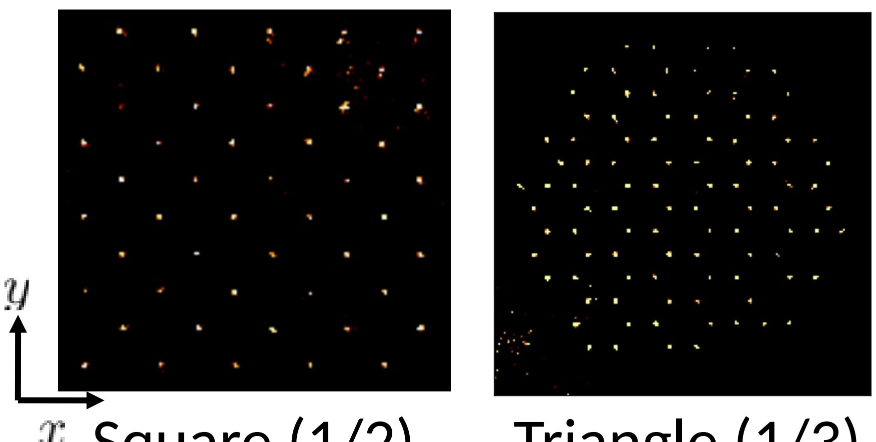
Antiferro $J_{ij} < 0$



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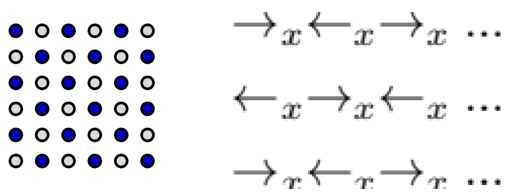

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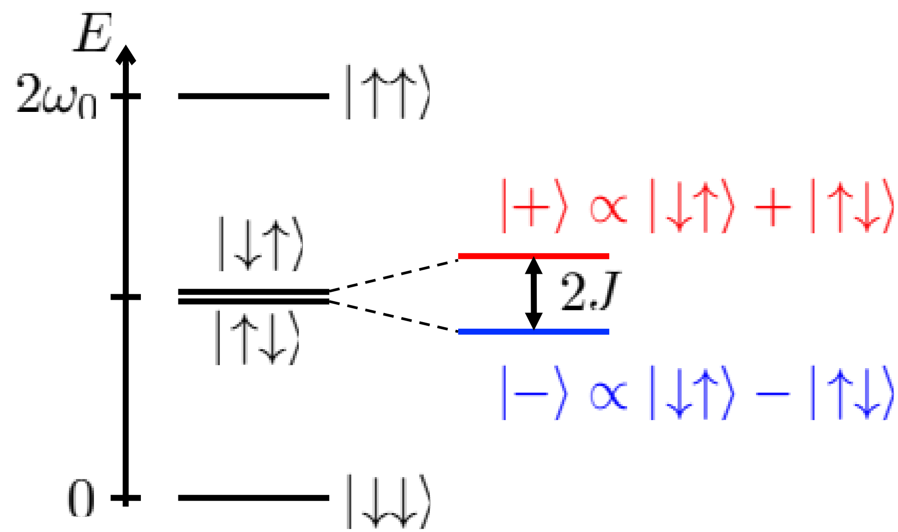
XY model

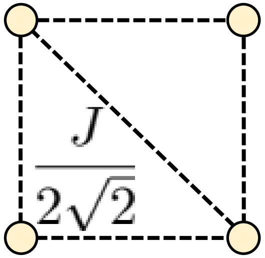
$$\hat{H} = \sum_{\langle i,j \rangle} J_{ij} (\hat{\sigma}_i^x \hat{\sigma}_j^x + \hat{\sigma}_i^y \hat{\sigma}_j^y)$$

$$= \sum_{\langle i,j \rangle} \frac{J_{ij}}{2} (\hat{\sigma}_i^+ \hat{\sigma}_j^- + \hat{\sigma}_i^- \hat{\sigma}_j^+)$$



Ground state (1/2) =
non-classical entangled state

XY model on a square lattice (1/2 filling)

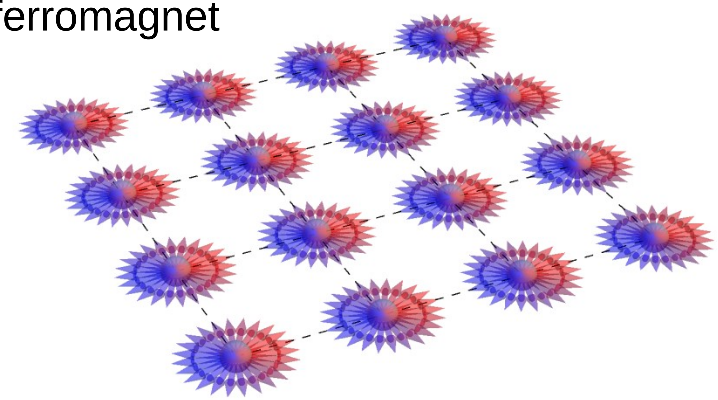


Ansätze wavefunctions

continuous $U(1)$ symmetry

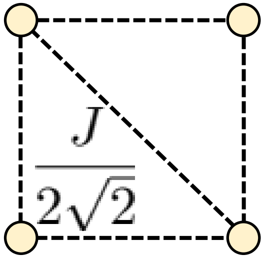
$M^z = \sum_i \sigma_i^z$ conserved

XY ferromagnet



$$|\mathrm{FM}\rangle_{\mathrm{XY}} \propto \int_0^{2\pi} \frac{\mathrm{d}\phi}{2\pi}\, \mathrm{e}^{-\mathrm{i}\phi \mathrm{S_z}} |\mathrm{FM}\rangle_{\mathrm{X}}$$

XY model on a square lattice (1/2 filling)



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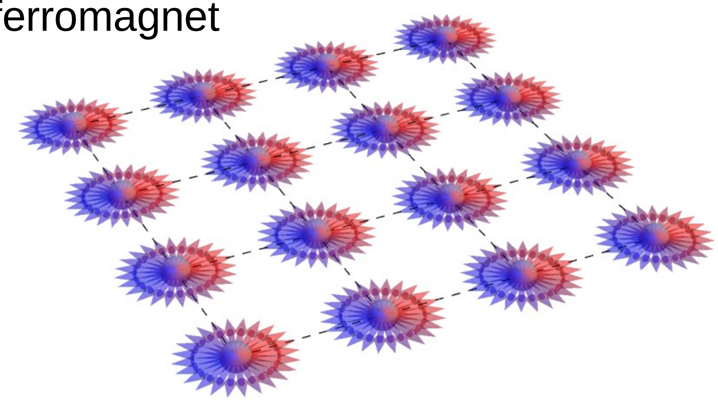

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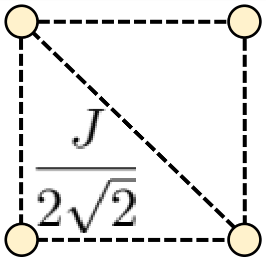
Expect: $\langle \hat{X} \rangle = 0$

$$\langle \hat{X}\hat{X} \rangle^F_{NN} > 0$$

$$\langle \hat{X}\hat{X} \rangle^F_{NNN} > 0$$

XY model on a square lattice (1/2 filling)



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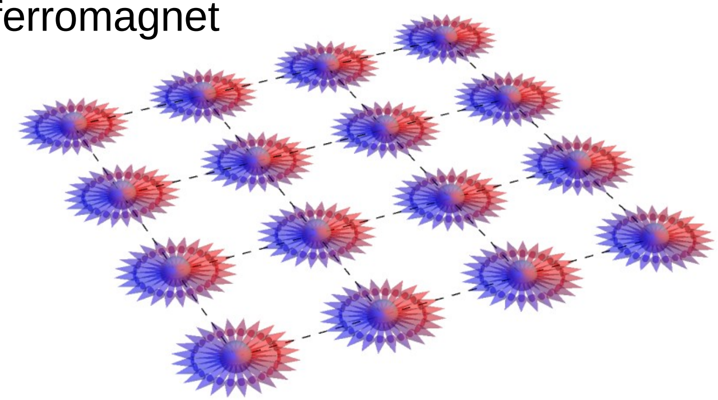
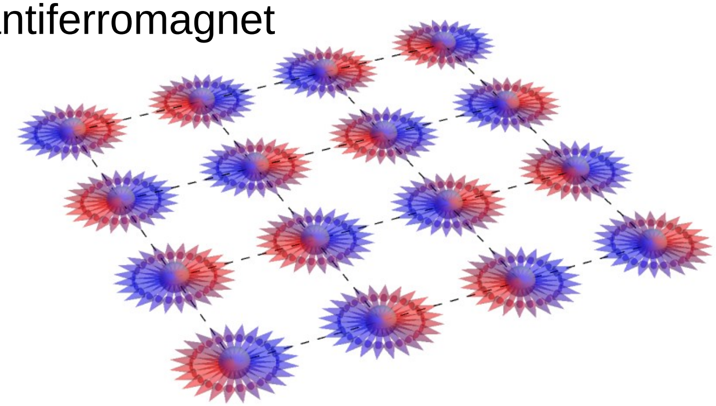


XY antiferromagnet



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$$|\mathrm{AFM}\rangle_{\mathrm{XY}} \propto \int_0^{2\pi} \frac{\mathrm{d}\phi}{2\pi}\, \mathrm{e}^{-\mathrm{i}\phi \mathrm{S_z}} |\mathrm{AFM}\rangle_{\mathrm{X}}$$

Expect: $\langle \hat{X} \rangle = 0$

$$\langle \hat{X}\hat{X} \rangle^F_{NN} > 0$$

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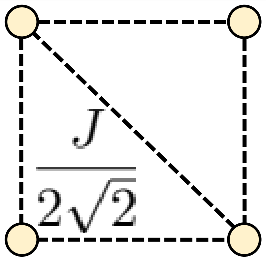
XY model on a square lattice (1/2 filling)



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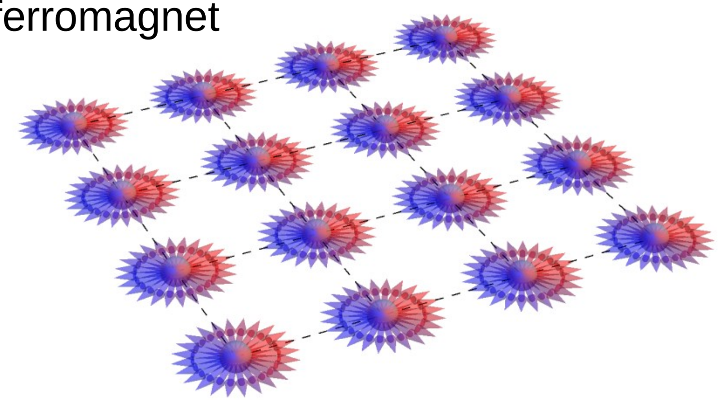

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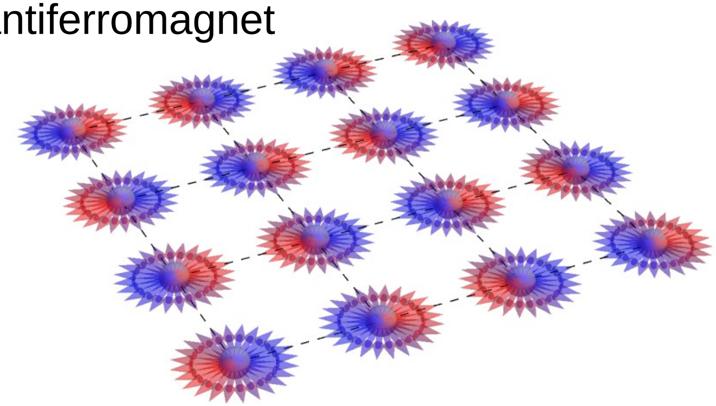

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Expect:

$$\langle \hat{X} \rangle = 0$$
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$$\langle \hat{X}\hat{X} \rangle^{F}_{NNN} > 0$$

$$\langle \hat{X} \rangle = 0$$
$$\langle \hat{X}\hat{X} \rangle^{AF}_{NN} < 0$$
$$\langle \hat{X}\hat{X} \rangle^{AF}_{NNN} > 0$$

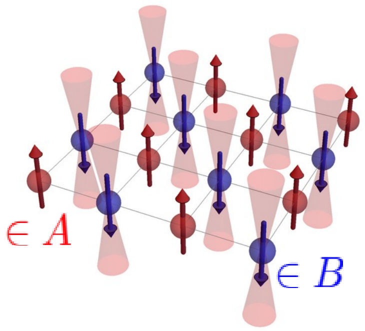
Experimental preparation of XY ferro- & antiferromagnets

Start from $$H_{\text{tot}} = \underbrace{-\frac{J}{2}\sum_{i<j}\frac{a^3}{r_{ij}^3}(\sigma_i^x\sigma_j^x + \sigma_i^y\sigma_j^y)}_{H_{\text{XY}}} + \underbrace{\hbar\delta\sum_{i\in B}\sigma_i^z}_{H_{\text{Z}}}$$

$(J/h \approx 0.8\,\text{MHz})$

staggered

1. Prepare a classical Néel state along *z*: checkerboard pattern



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

Sørensen *et al.*, PRA 81, 061603(R) (2010)

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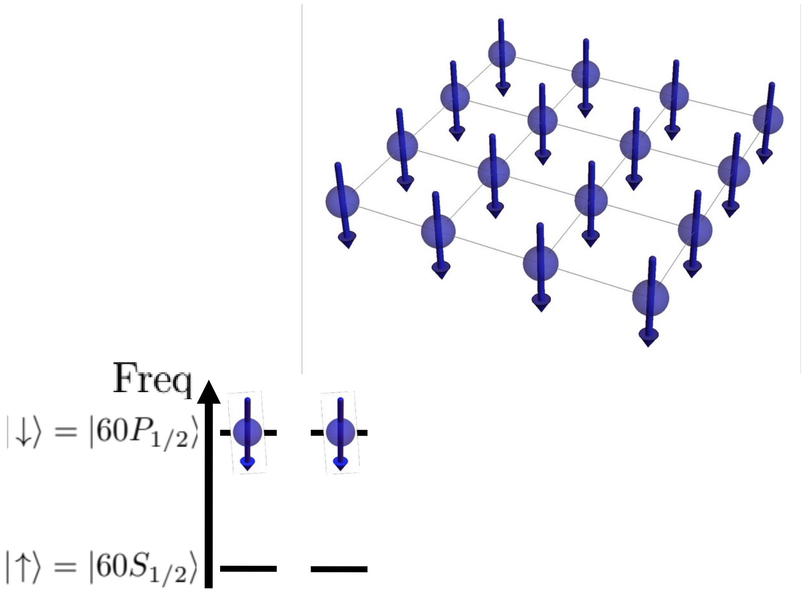

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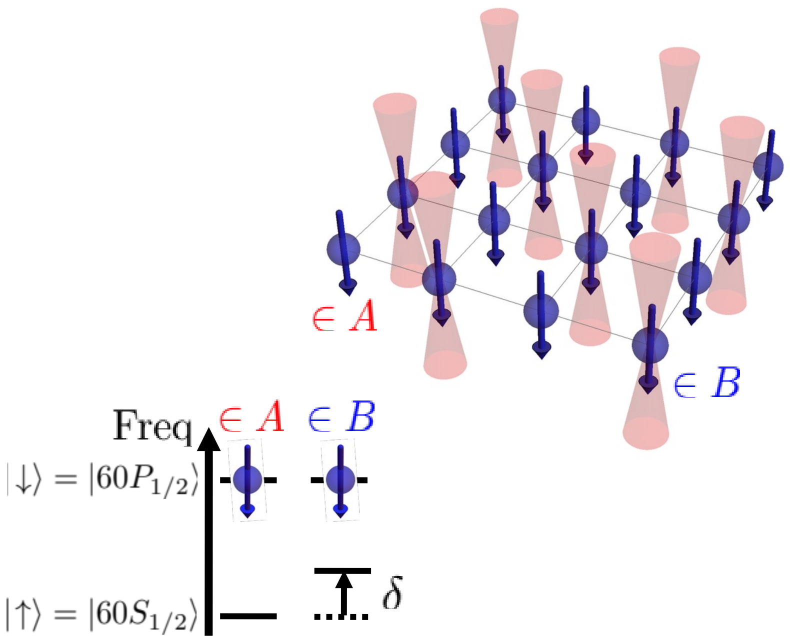

apply local light-shifts

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

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staggered

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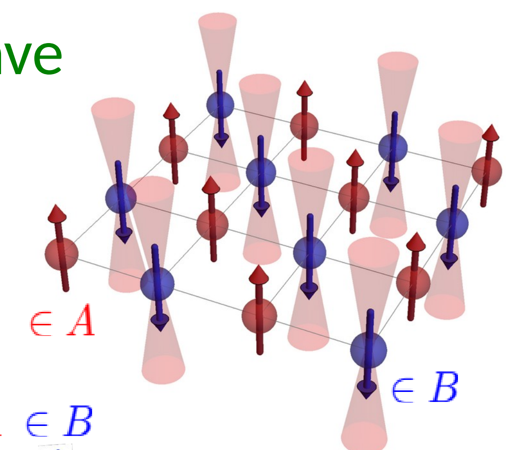
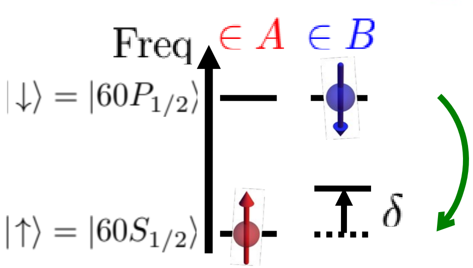
Microwave





Microwave on resonance

Fidelity (>90%/atom)

apply local light-shifts

+

Microwave

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

Sørensen *et al.*, PRA 81, 061603(R) (2010)

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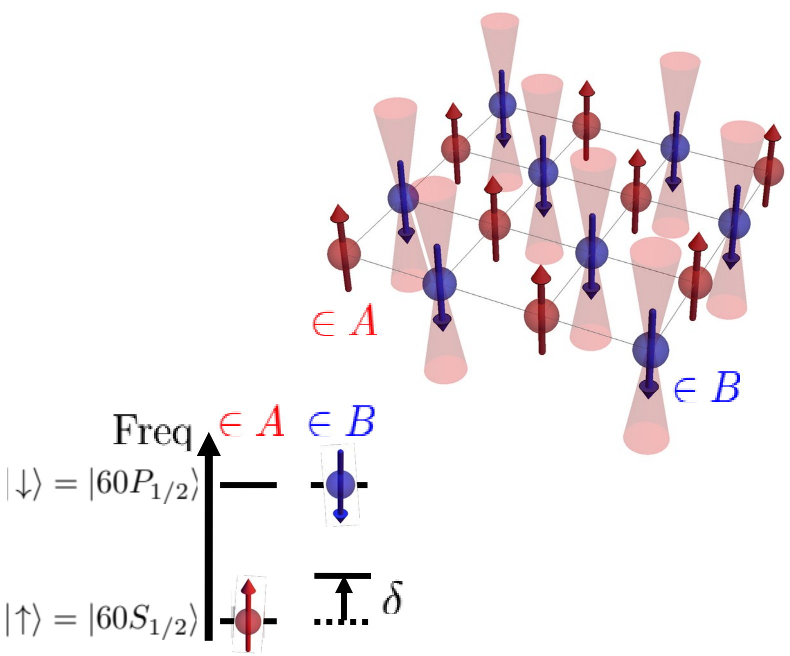
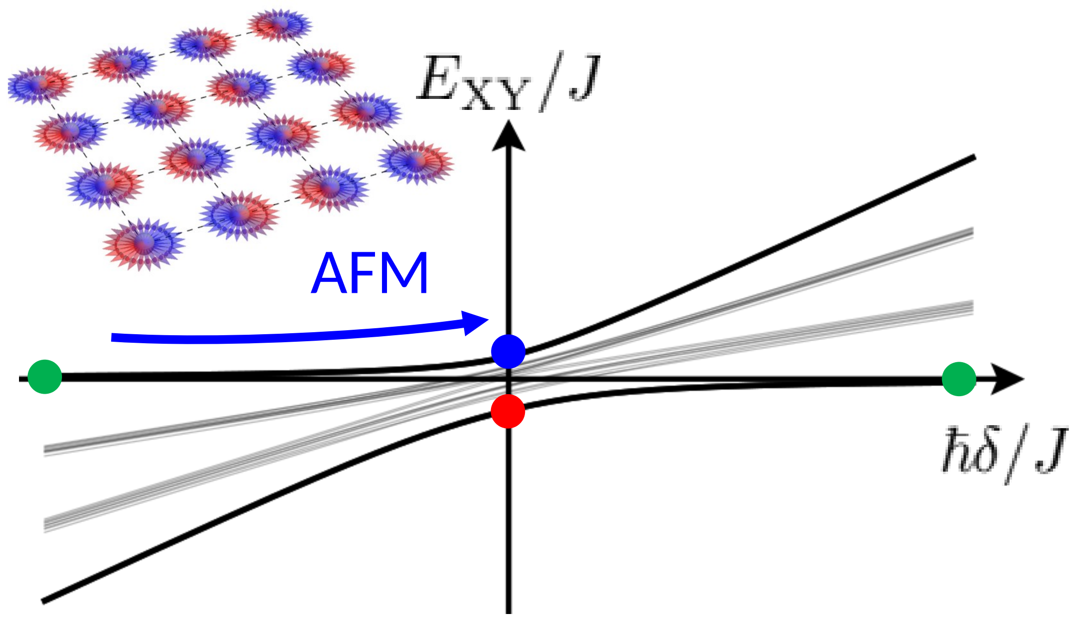
$(J/h \approx 0.8\,\mathrm{MHz})$

$H_{\rm XY}$ $H_{\rm Z}$

staggered

2. Adiabatically decrease to prepare the XY AFM / FM





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H_{XY} $\qquad$ H_{Z}

staggered

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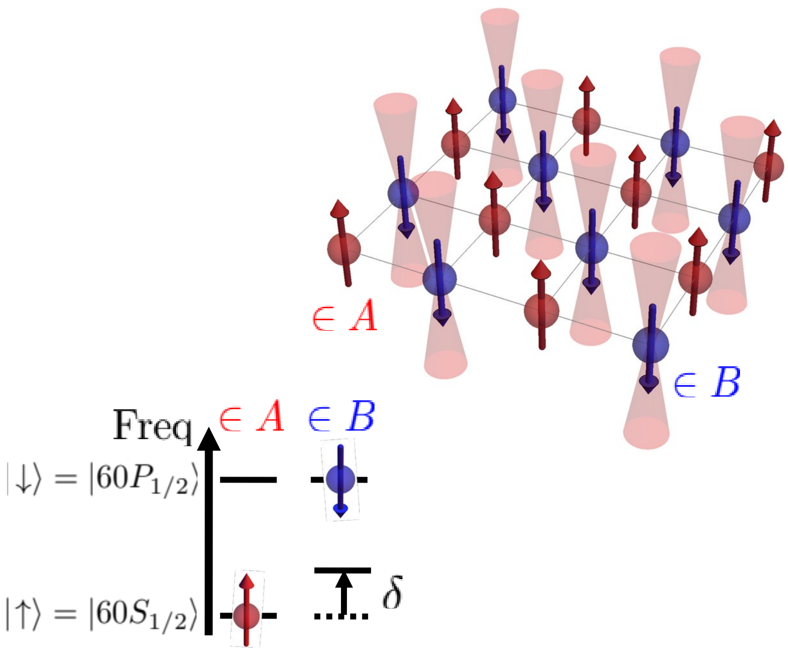
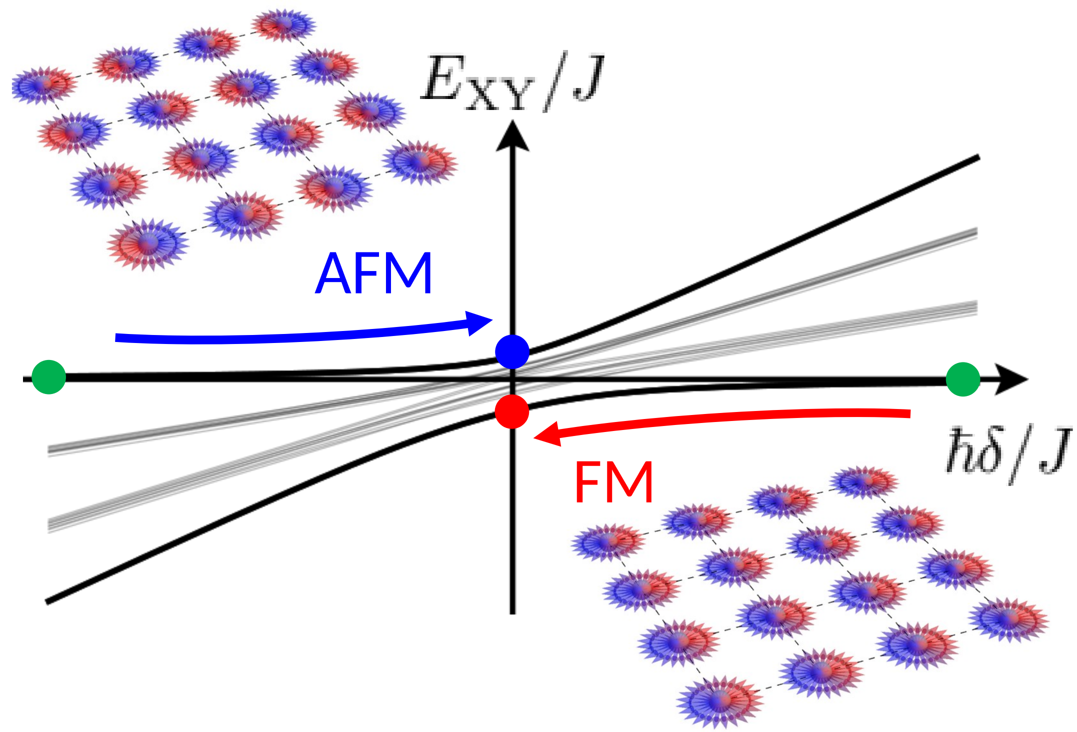
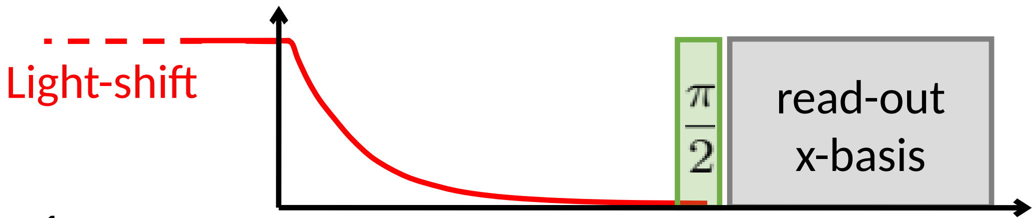




C. Chen *et al.*, Nature **616**, 691 (2023)

Sørensen *et al.*, PRA 81, 061603(R) (2010)

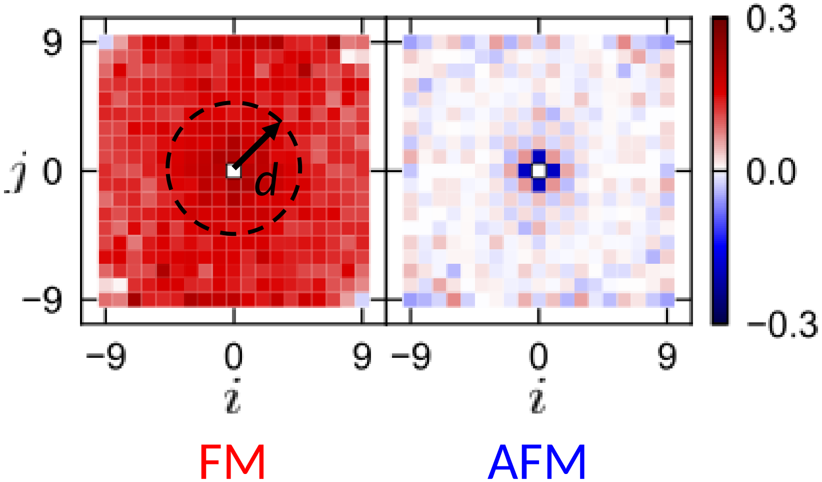
Observation of Long-Range FM order

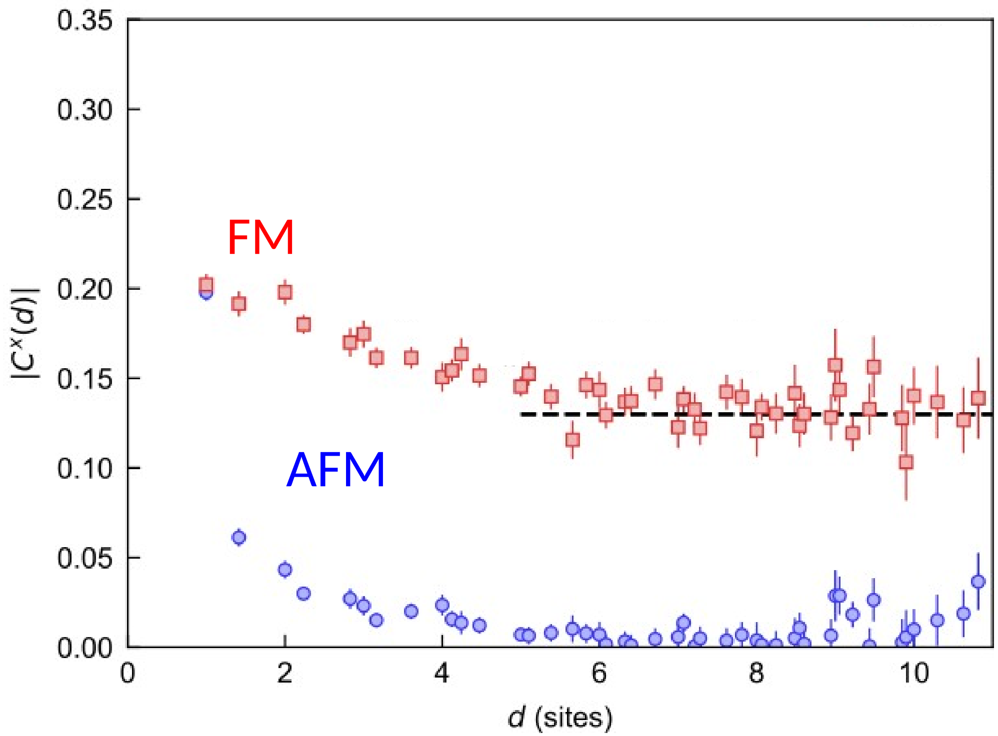


10 x 10 = 100 atoms

t = 1 s

$$C^x_{ij} = \langle \sigma^x_i \sigma^x_j \rangle - \langle \sigma^x_i \rangle \langle \sigma^x_j \rangle$$





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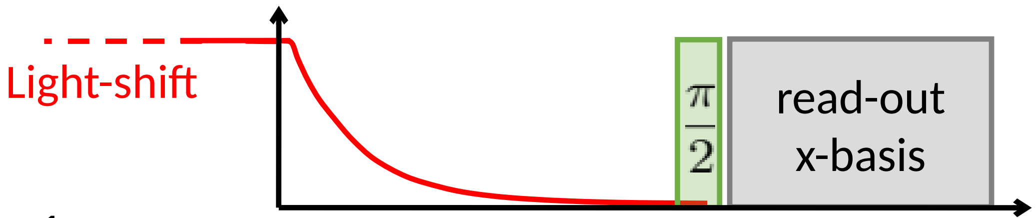

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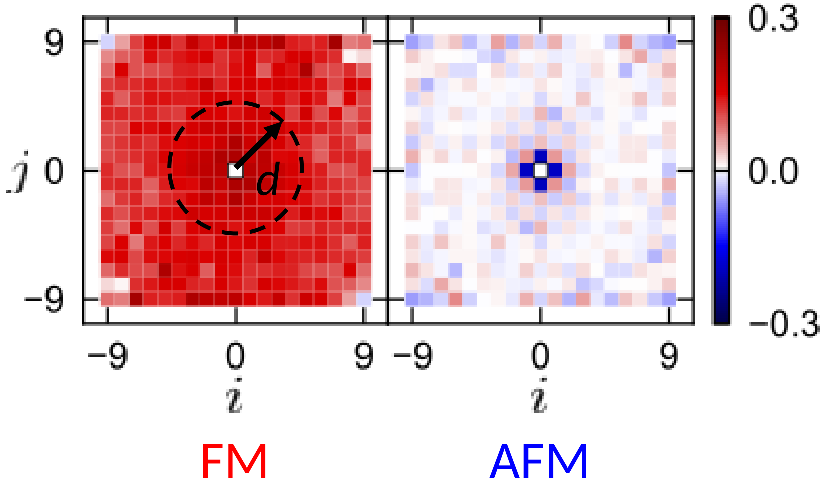
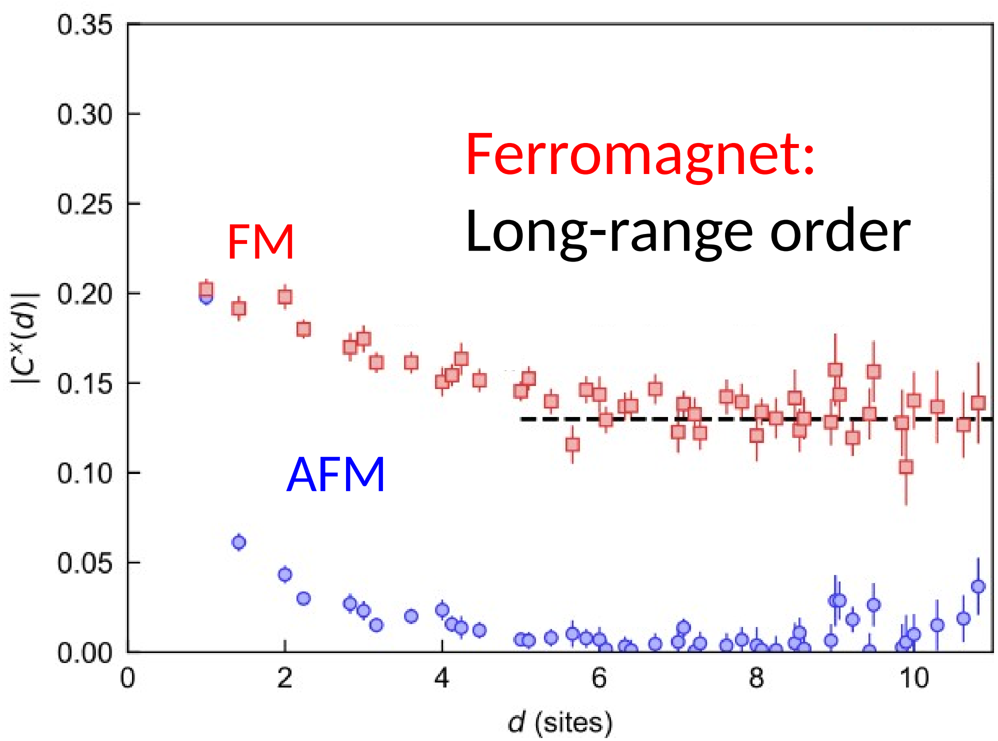




Antiferromagnet: LRO destabilized by frustration

Important role of $1/r^3$ interaction

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

Feng *et al.*, Nature 623, 713 (2023)

Sbierski *et al.*, arXiv:2305.03673

Spin squeezing from a non-linear Hamiltonian

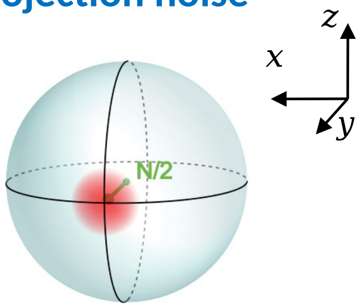
Protocol:

Collective spin: $\hat{J}_\alpha = \sum_{i=1}^{N} \hat{\sigma}_i^\alpha$

1) Initialize: $|\psi_0\rangle = |\rightarrow, \rightarrow ...\rangle_y = (|\uparrow\rangle + i|\downarrow\rangle)^{\otimes N}$

"Coherent spin state"

Quantum projection noise



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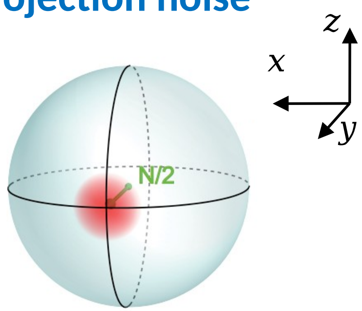

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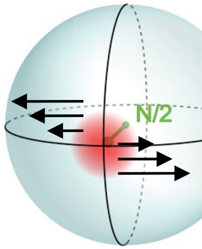

2) Time evolve with *H*: $|\psi(t)\rangle = e^{-iHt}|\psi_0\rangle$

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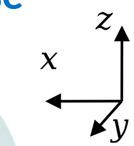

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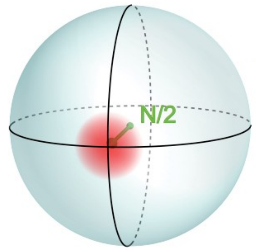

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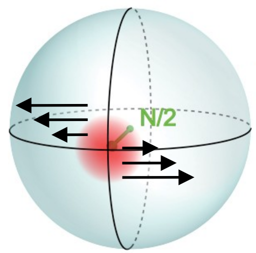
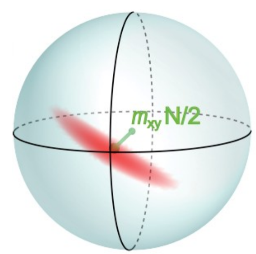


3) Measure squeezing at time *t*:



Improve phase resolution by reshaping quantum spin projection noise

$$\Delta J_x \Delta J_z \geq \frac{|\langle J_y \rangle|}{2}$$

Spin squeezing in OAT vs XY

Ideal case:

Kitagawa, Masahiro & Ueda, Masahito, PRA 47(6), 1993

One axis twisting (OAT):

$$H_{\mathrm{OAT}} = \chi J_z^2 = \chi \sum_{i,j} \hat{\sigma}_i^z \hat{\sigma}_j^z$$

all-to-all

Spin squeezing in OAT vs XY

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One axis twisting (OAT): $H_{\mathrm{OAT}} = \chi J_z^2 = \chi \sum_{i,j} \hat{\sigma}_i^z \hat{\sigma}_j^z$ all-to-all

Intuition: **Dipolar XY: "same" structure:**

$$H_{\text{all-to-all XY}} \propto \sum_{i<j} (\sigma_x^i \sigma_x^j + \sigma_y^i \sigma_y^j + \sigma_z^i \sigma_z^j) - \sum_{i<j} \sigma_z^i \sigma_z^j$$

$$H_{\text{all-to-all XY}} = H_{\text{Heisenberg}} - H_{\text{OAT}}$$

Commutes with H_{OAT}
$|\rightarrow, \rightarrow \ldots\rangle_y$ is an eigenstate

Drives the dynamics

Spin squeezing in OAT vs XY

Ideal case:

Kitagawa, Masahiro & Ueda, Masahito, PRA 47(6), 1993

One axis twisting (OAT): $H_{\mathrm{OAT}} = \chi J_z^2 = \chi \sum_{i,j} \hat{\sigma}_i^z \hat{\sigma}_j^z$ **all-to-all**

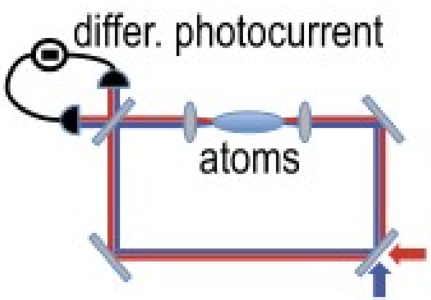
Intuition: **Dipolar XY: "same" structure:**

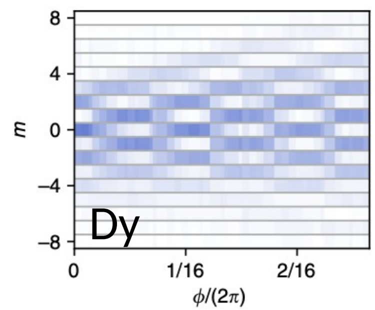
Is 1/r^3 long-range enough to generate squeezing?

Experimental observations of spin squeezing

Pezzé *et al.*, RMP 2018

Hot / cold atomic vapors

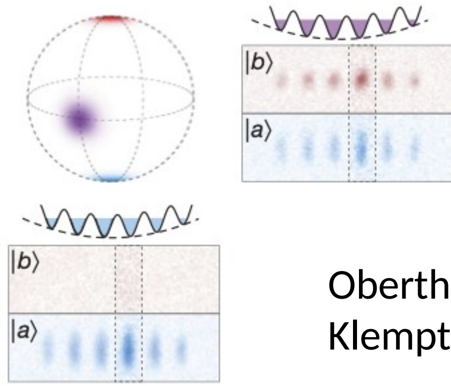




Nat Comm 2018

Polzik (1999), Giacobino, Mitchell, Nascimbene…

Bose-Einstein condensate (OAT)

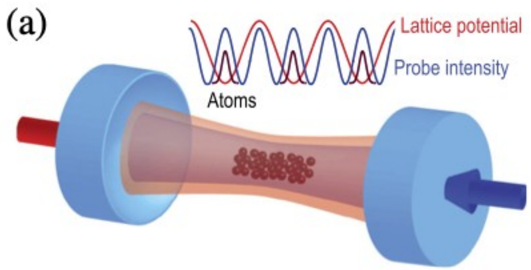


Nature 2010

Oberthaler, Treutlein, Klempt, Reichel, …

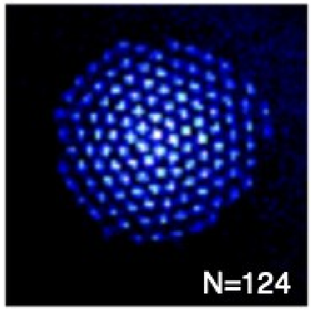
Cavity QED + cold atoms (OAT)

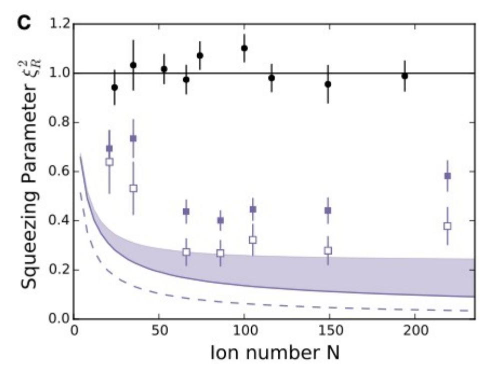
Kasevich, Nature 2016



Vuletic, Kasevich, Thompson (JILA), Je, Schleier-Smith…

Ion crystal (~OAT)

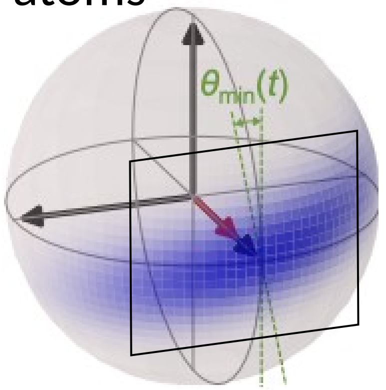


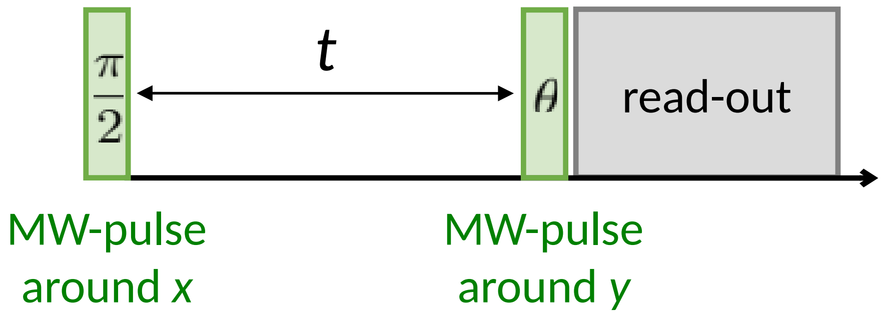


Bollinger, Science 2016

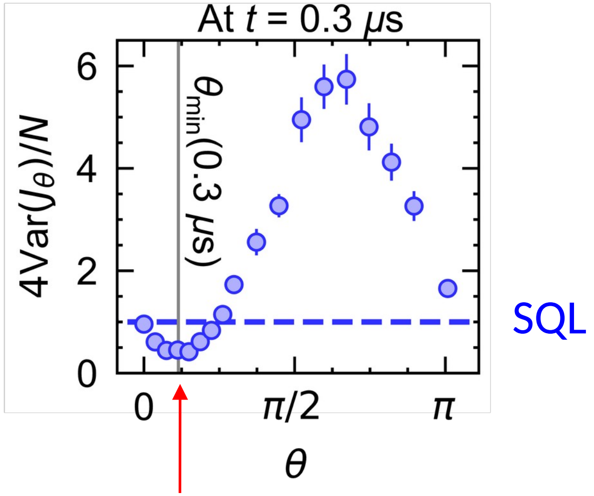
Dipolar squeezing with Rydberg atoms

6 x 6 atoms





$$J_\theta = \cos(\theta)J_z + \sin(\theta)J_x$$

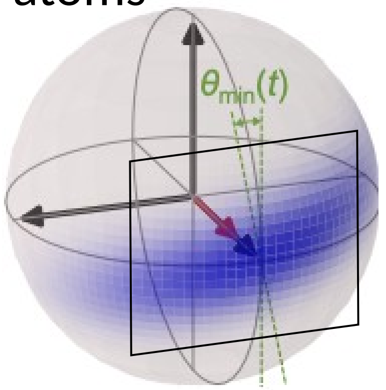


Minimum variance!

G. Bornet *et al.*, Nature **621**, 728 (2023)

Dipolar squeezing with Rydberg atoms

6 x 6 atoms



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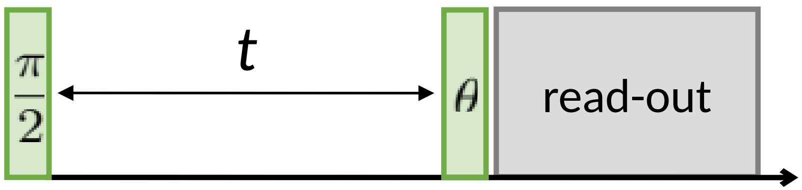
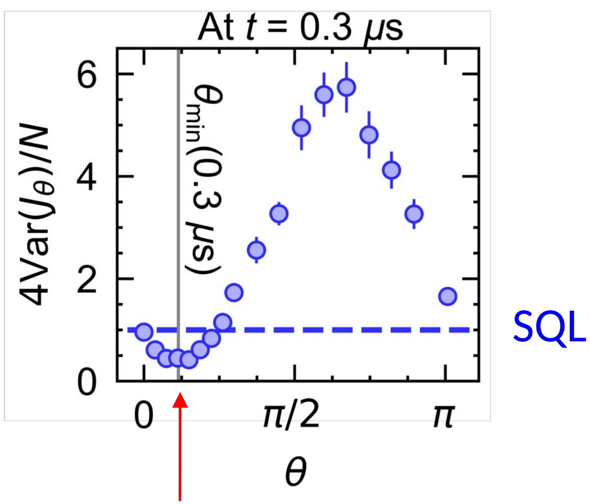
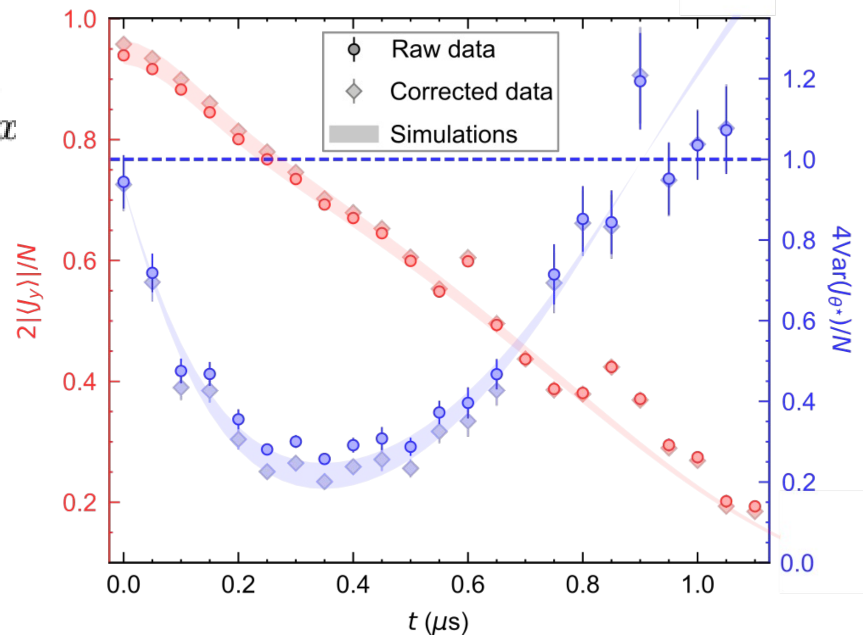


MW-pulse around *x*

MW-pulse around *y*



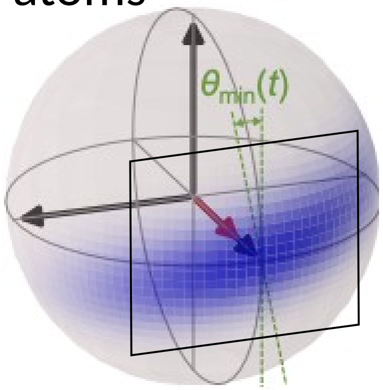


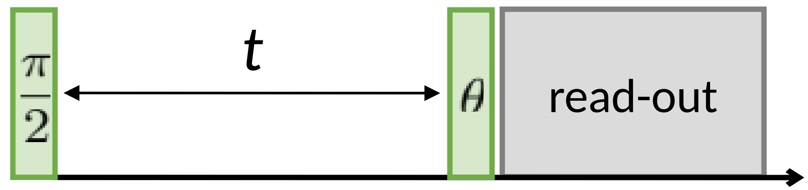
Minimum variance!

G. Bornet *et al.*, Nature **621**, 728 (2023)

Dipolar squeezing with Rydberg atoms

6 x 6 atoms





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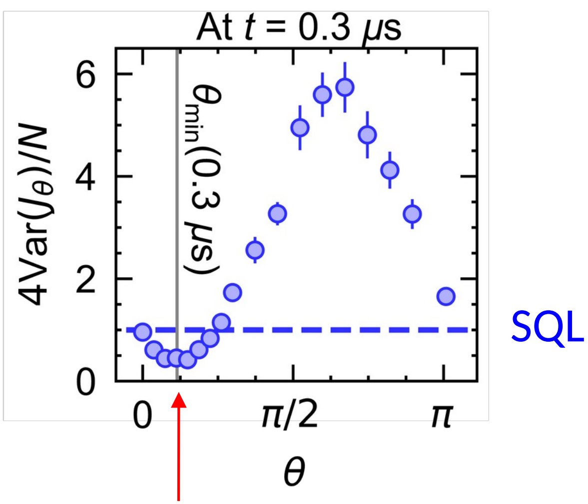
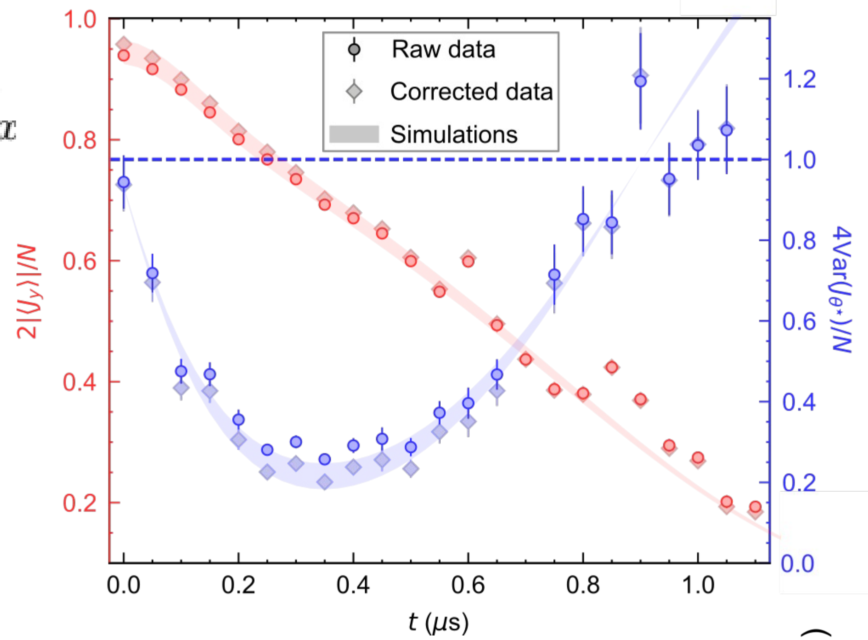
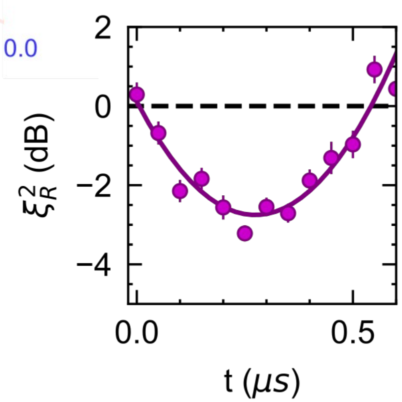




Minimum variance!

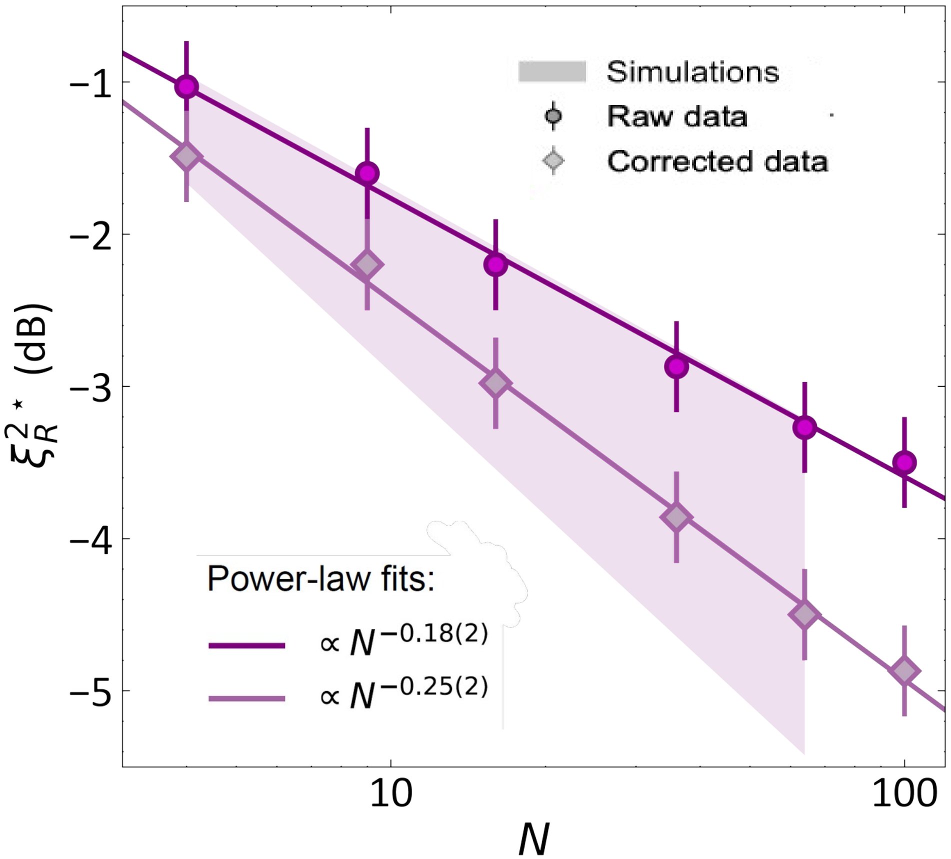
$$\xi_R^2(t) = \frac{N \min_\theta \left(\mathrm{Var}\left(J_\theta\right)\right)}{\langle J_y \rangle^2}$$



G. Bornet *et al*., Nature **621**, 728 (2023)

Wineland, PRA 1994

Scaling of squeezing with atom number



Theory:

Comparin *et al.*, PRL 129, 150503 (2022)
Block *et al.*, arXiv:2301.09636
Roscilde *et al.*, PRB 108.155130 (2023)

Other platforms:

Rydberg dressing:
Hines *et al.*, PRL 131, 063401 (2023)
Eckner *et al.*, Nature 621 (2023)

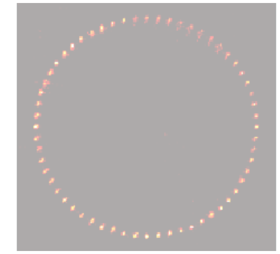
Ions:
Franke *et al.*, Nature 621 (2023)

Conclusion: scalable squeezing with dipolar interaction

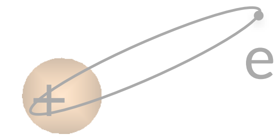
G. Bornet *et al.*, Nature **621**, 728 (2023)

Outline

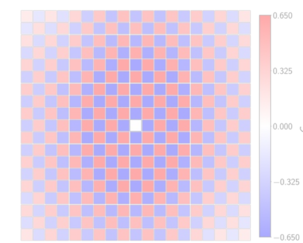
1. **Arrays of individual atoms**



2. **Rydberg atoms and their interactions**



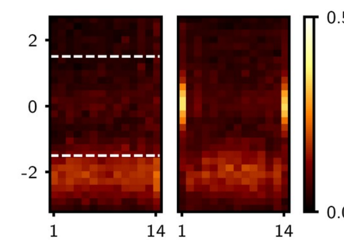
3. **Examples of quantum simulations**



   A. Exploration of phase diagrams

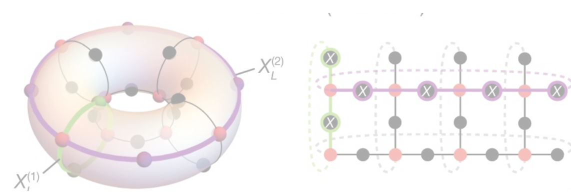
   B. Out-of-Equilibrium dynamics

   C. Ground state preparation & squeezing



   D. Synthetic Topological matter

4. **Digital quantum computing**



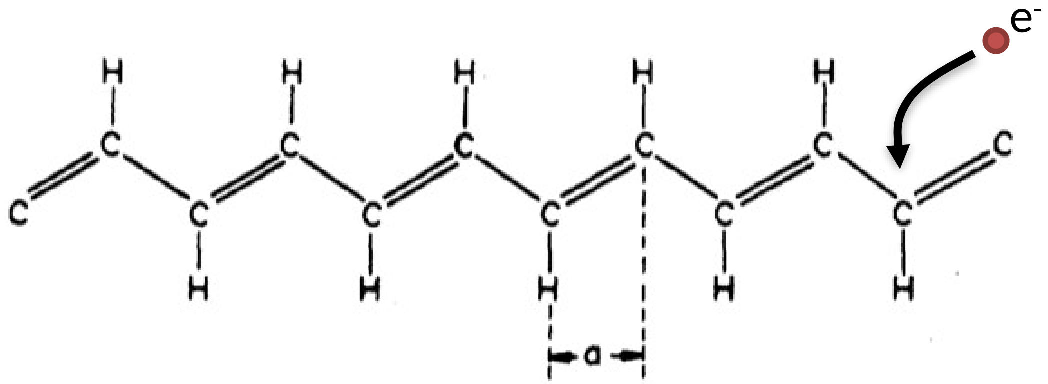
The Su-Schrieffer-Heeger model

- Introduced to explain conductivity in polymers

VOLUME 42, NUMBER 25 PHYSICAL REVIEW LETTERS 18 JUNE 1979

Solitons in Polyacetylene

W. P. Su, J. R. Schrieffer, and A. J. Heeger
Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania 19104

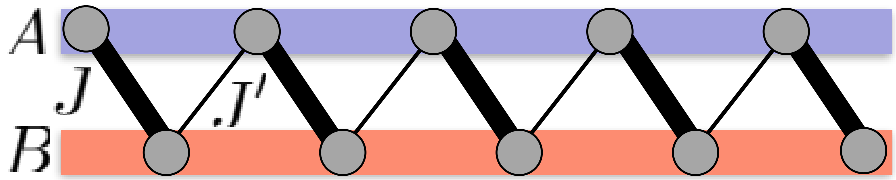


- Now, considered as simplest example of topological model

Asboth, arXiv:1509.02295, Cooper, arXiv:1803.00249

- **Goal:** build a synthetic SSH system to explore role
    - Symmetries
    - Interactions
    -

The Su-Schrieffer-Heeger model



Model: tight-binding

dimerization: $J > J'$

Asboth, arXiv:1509.02295
Cooper, arXiv:1803.00249

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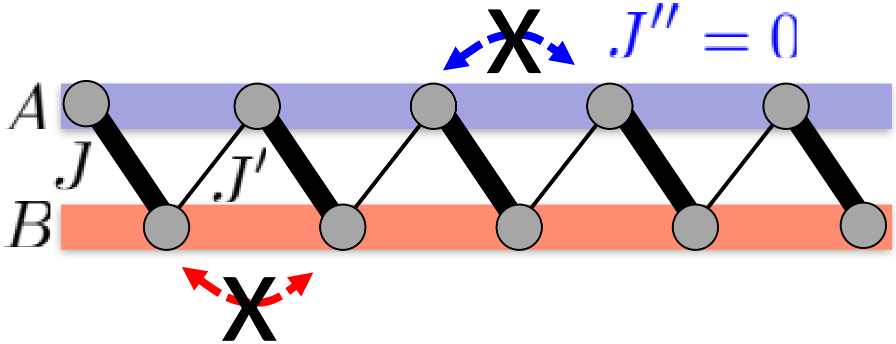


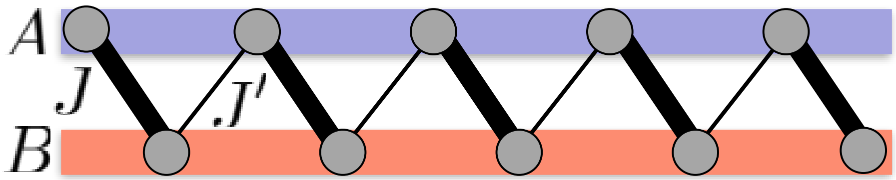
Model: tight-binding

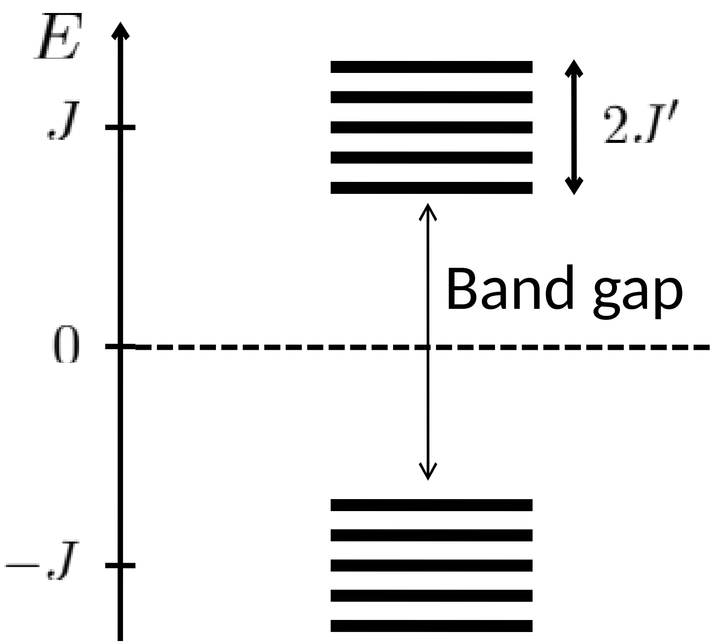
dimerization: $J > J'$

Sub-lattice symmetry = symmetric **single particle** spectrum

Asboth, arXiv:1509.02295
Cooper, arXiv:1803.00249

Single-particle SSH spectrum (finite chain): edge states





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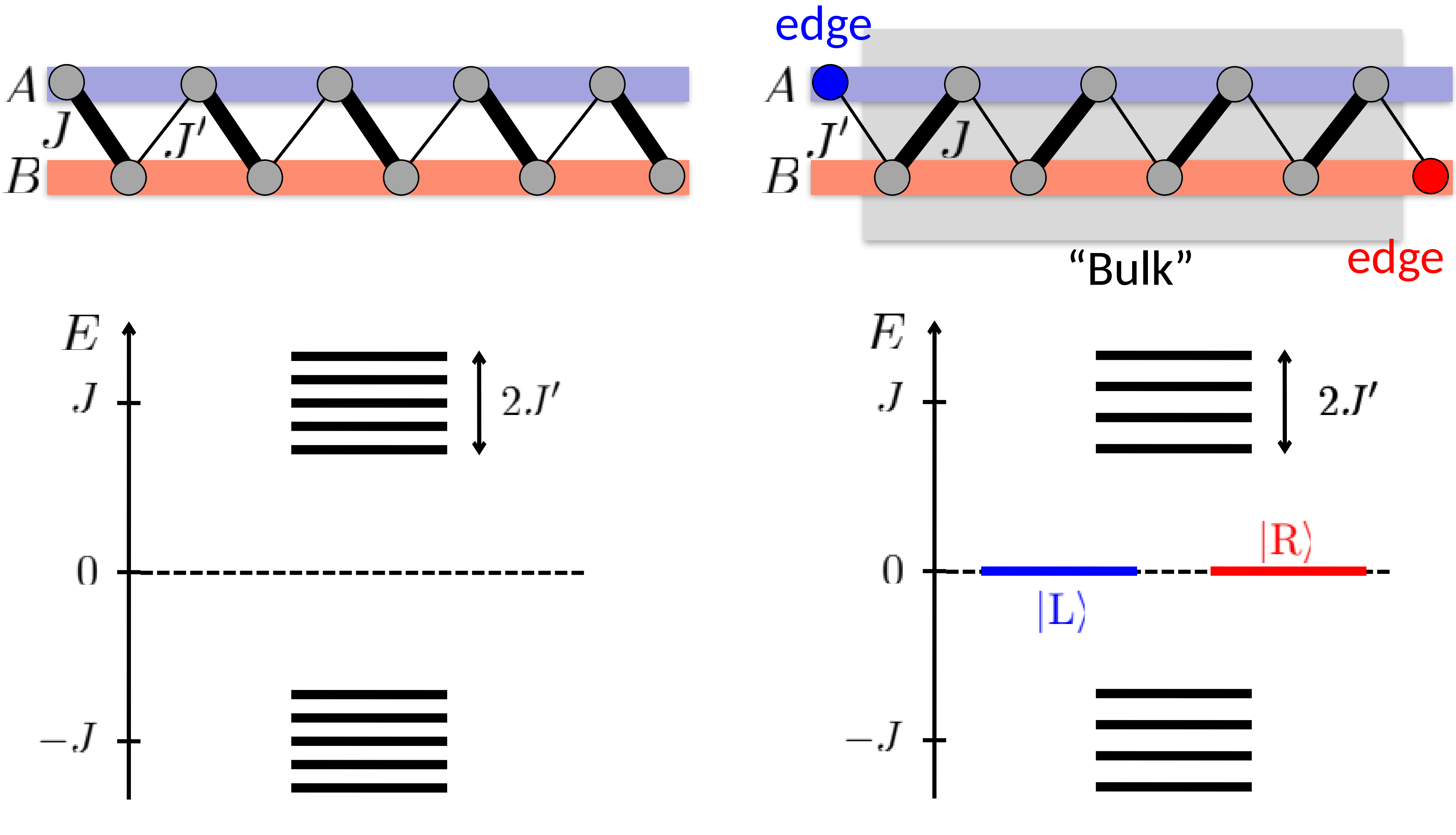

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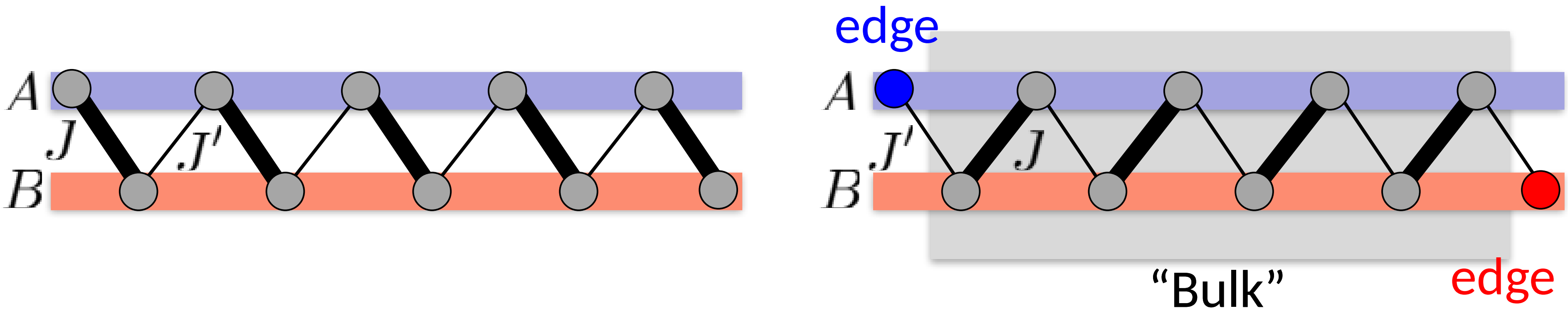

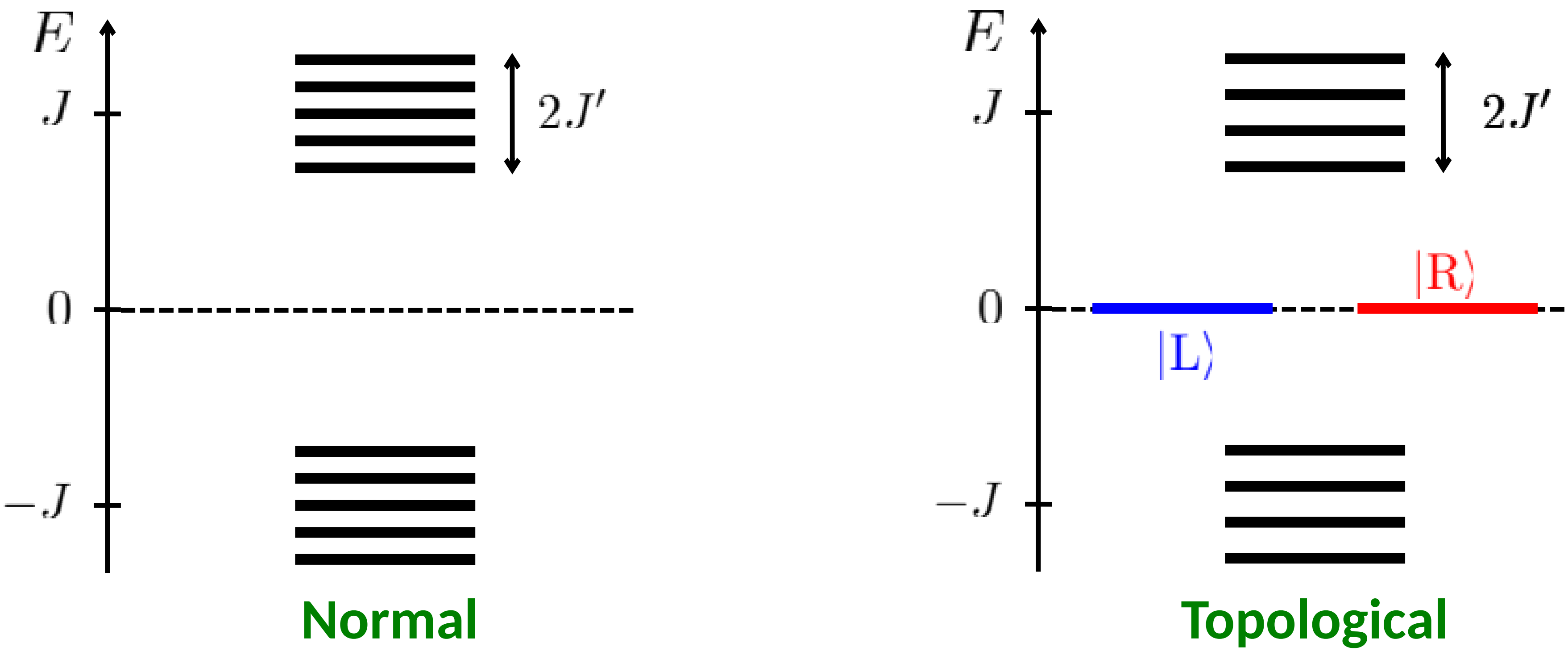

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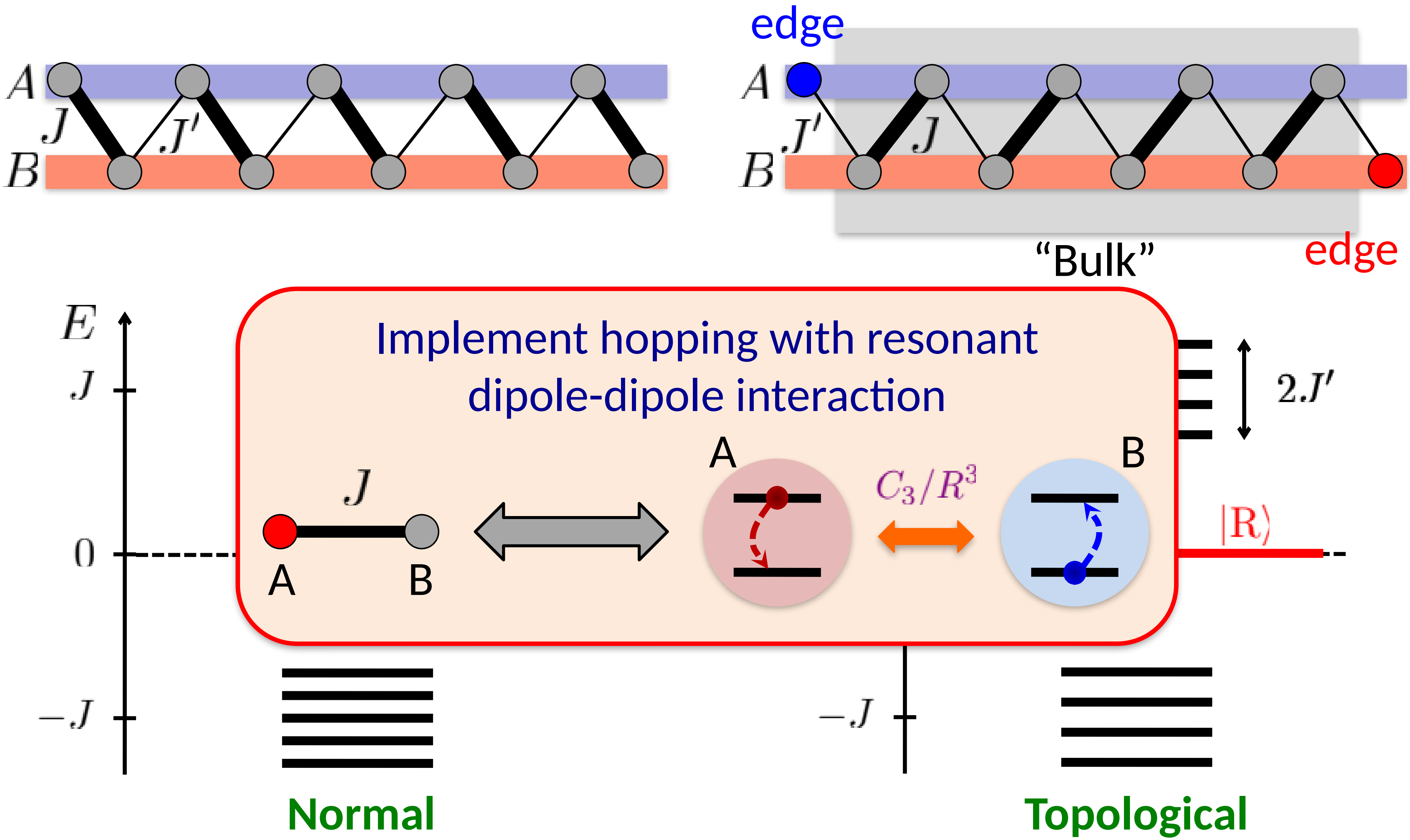
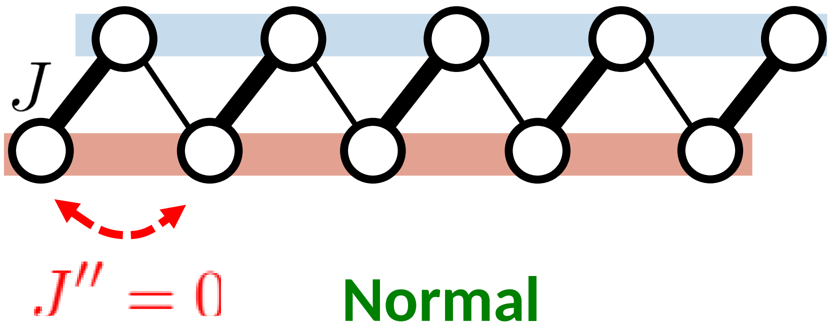
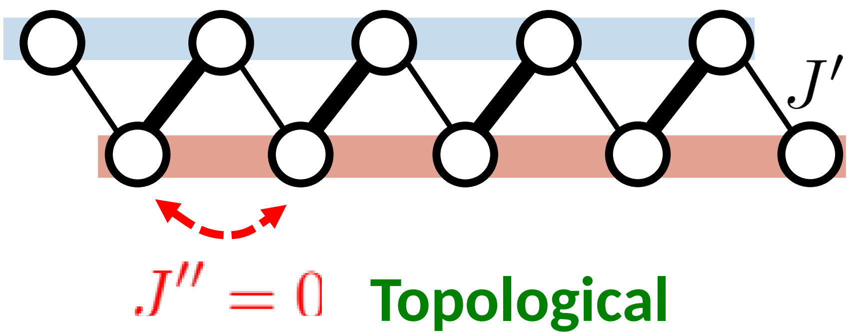


Asboth, arXiv:1509.02295
Cooper, arXiv:1803.00249

Implementation of SSH spin chain with Rydberg atoms

Science **365**, 775 (2019)





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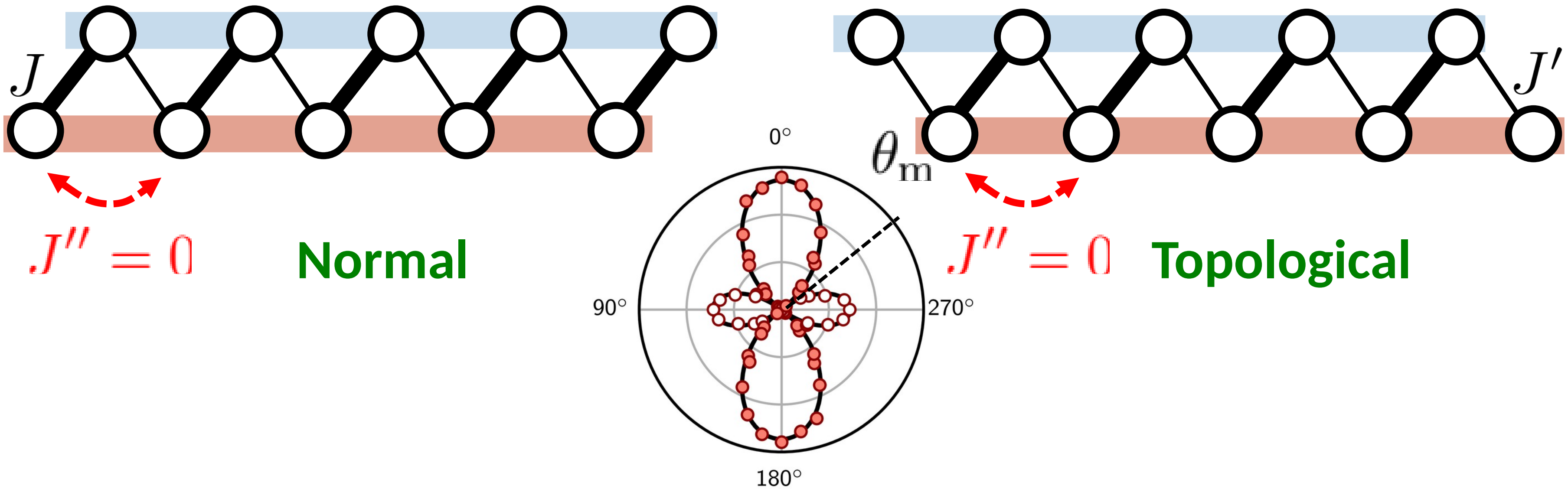
Science **365**, 775 (2019)



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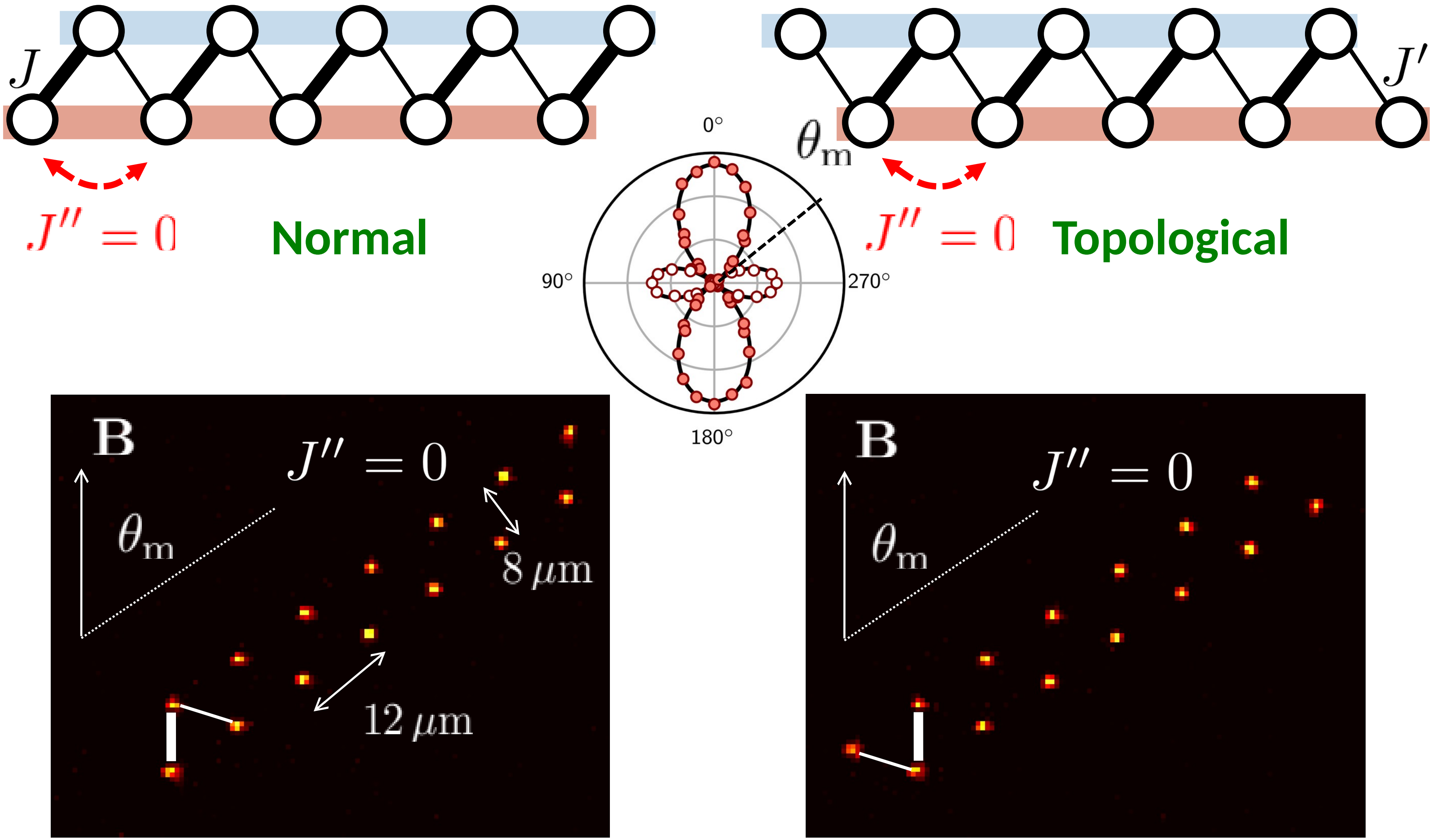
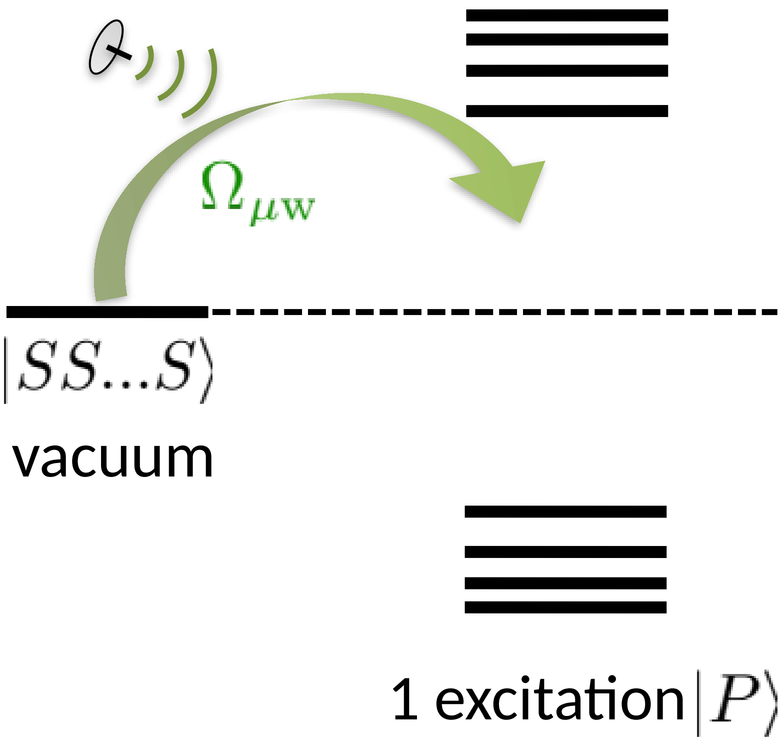


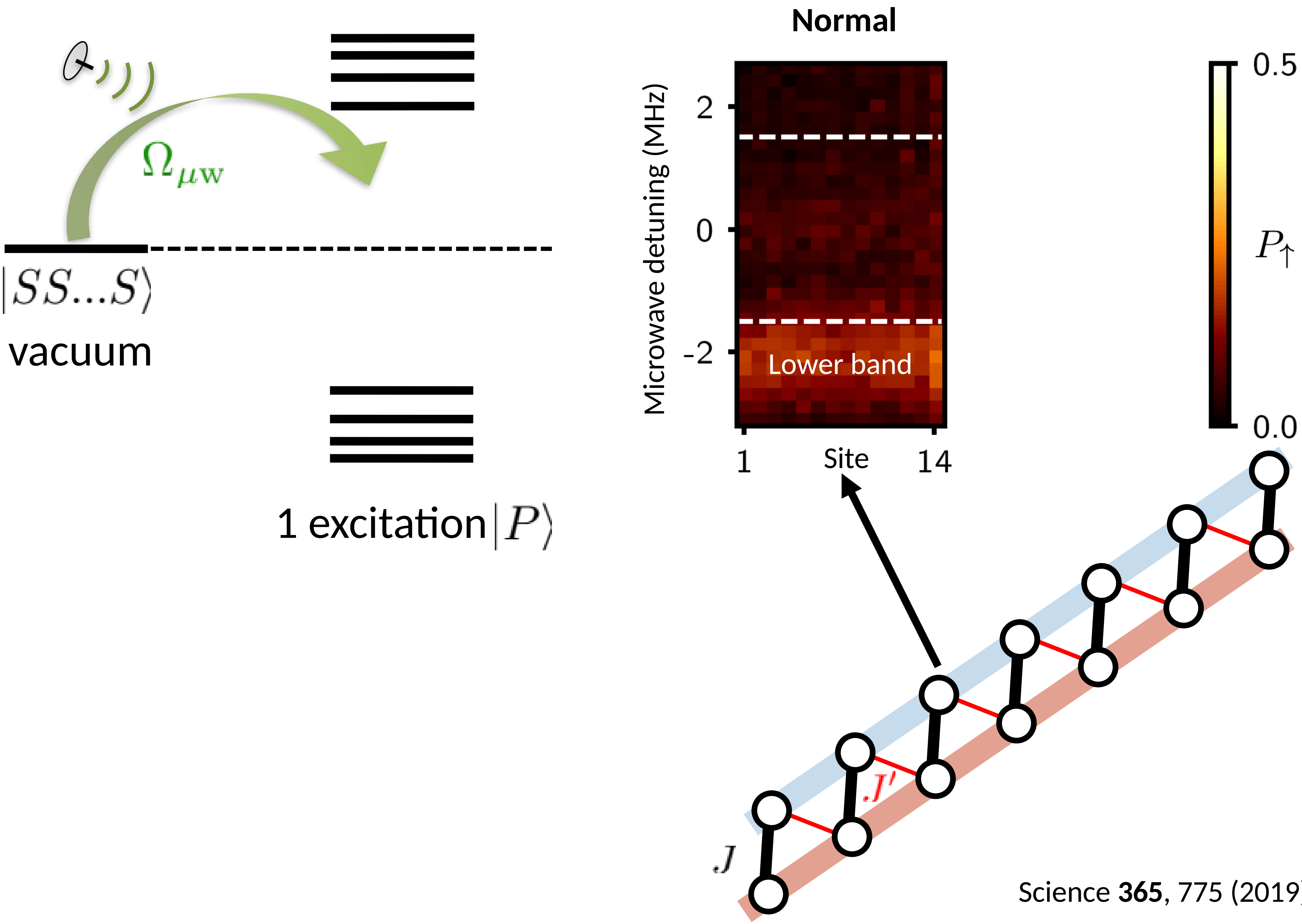
$J/h = 2.4\,\text{MHz} \quad J'/h = -0.9\,\text{MHz}$

Probing the single-particle SSH spectrum



Science **365**, 775 (2019)

Probing the single-particle SSH spectrum



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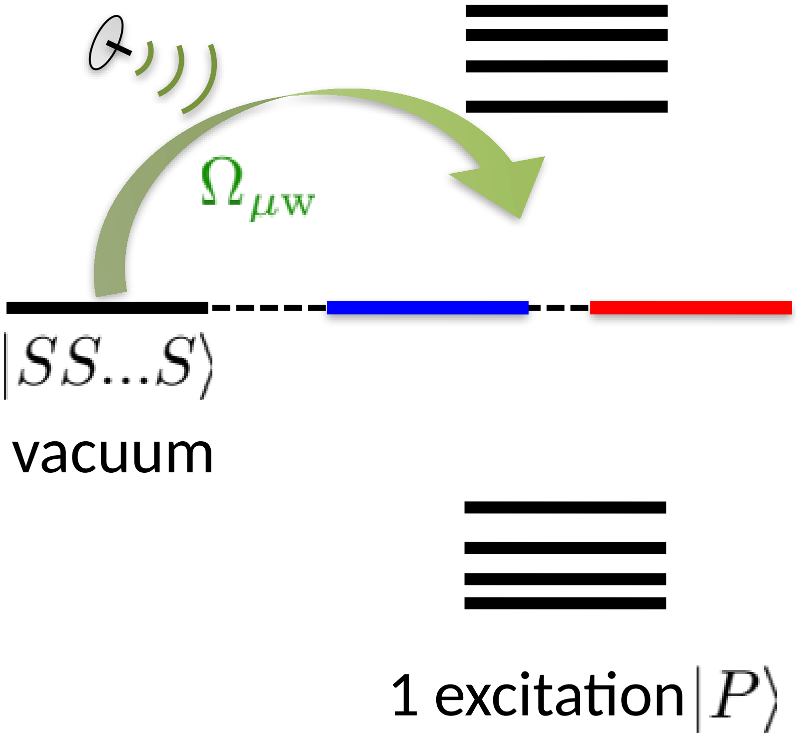

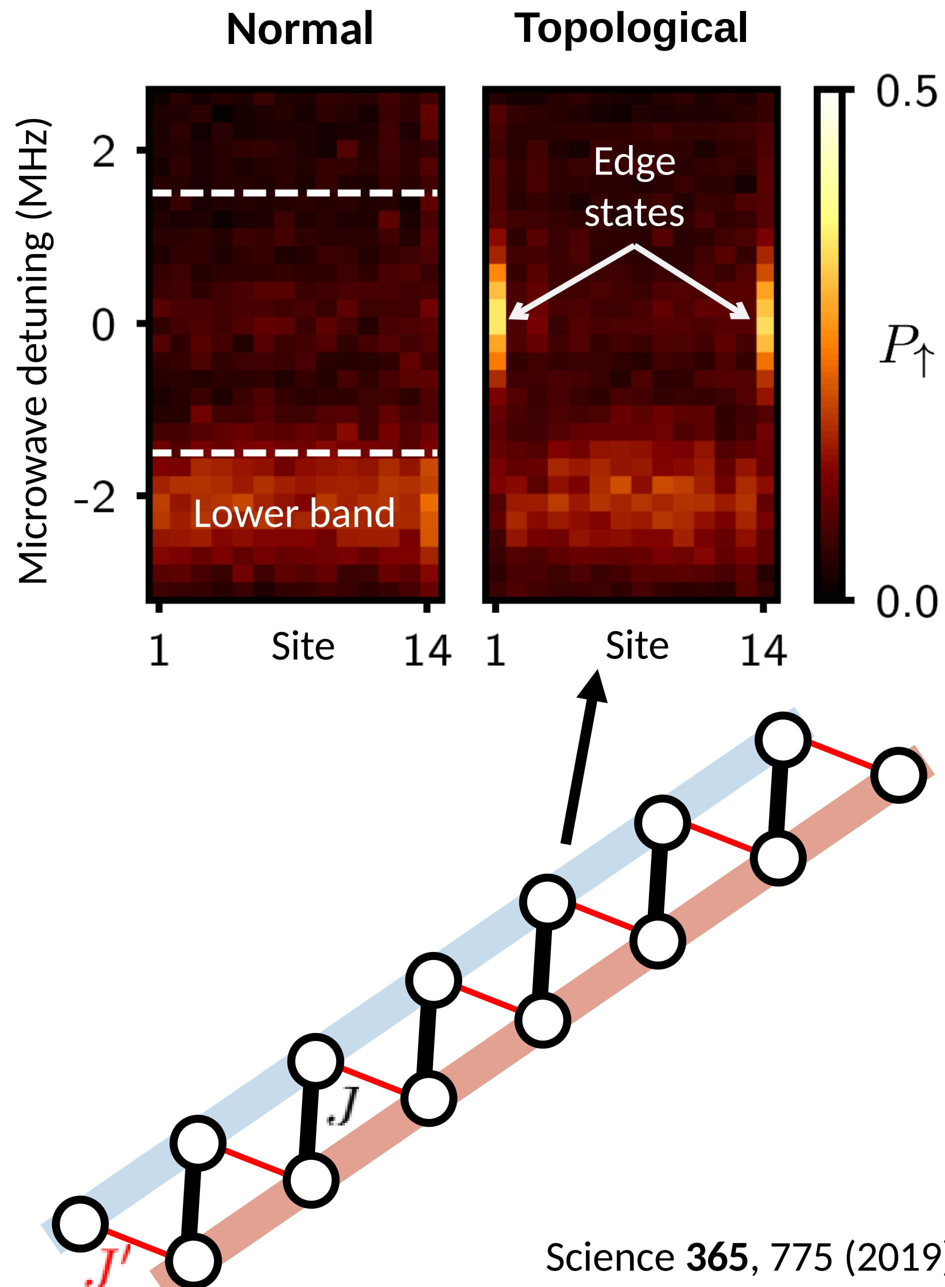

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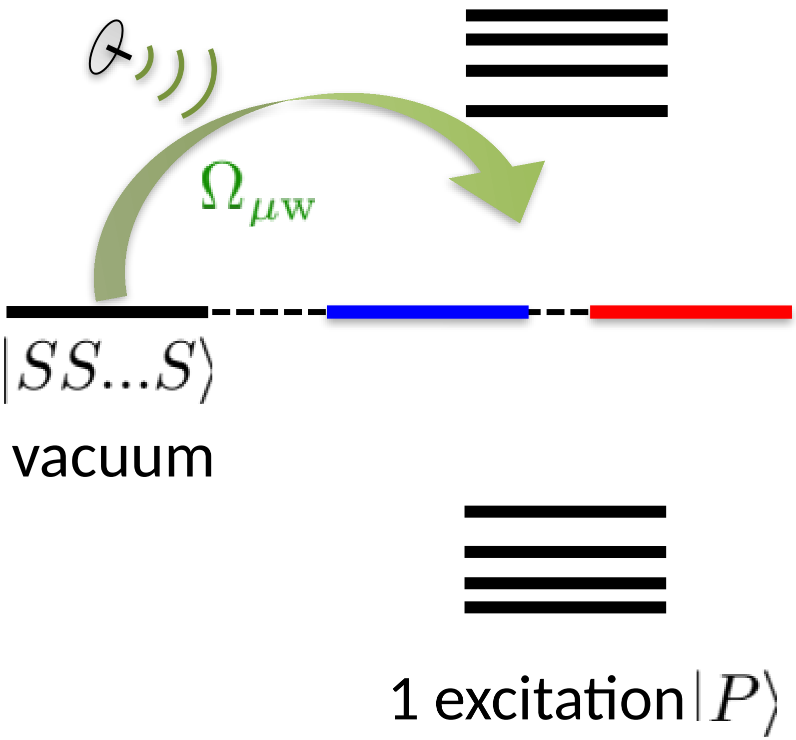

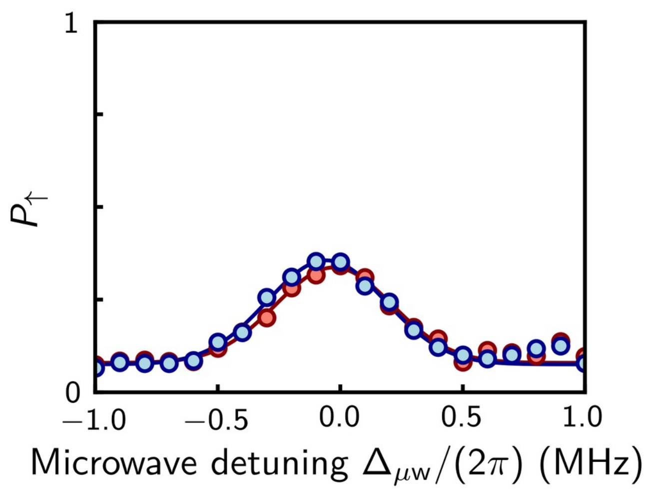

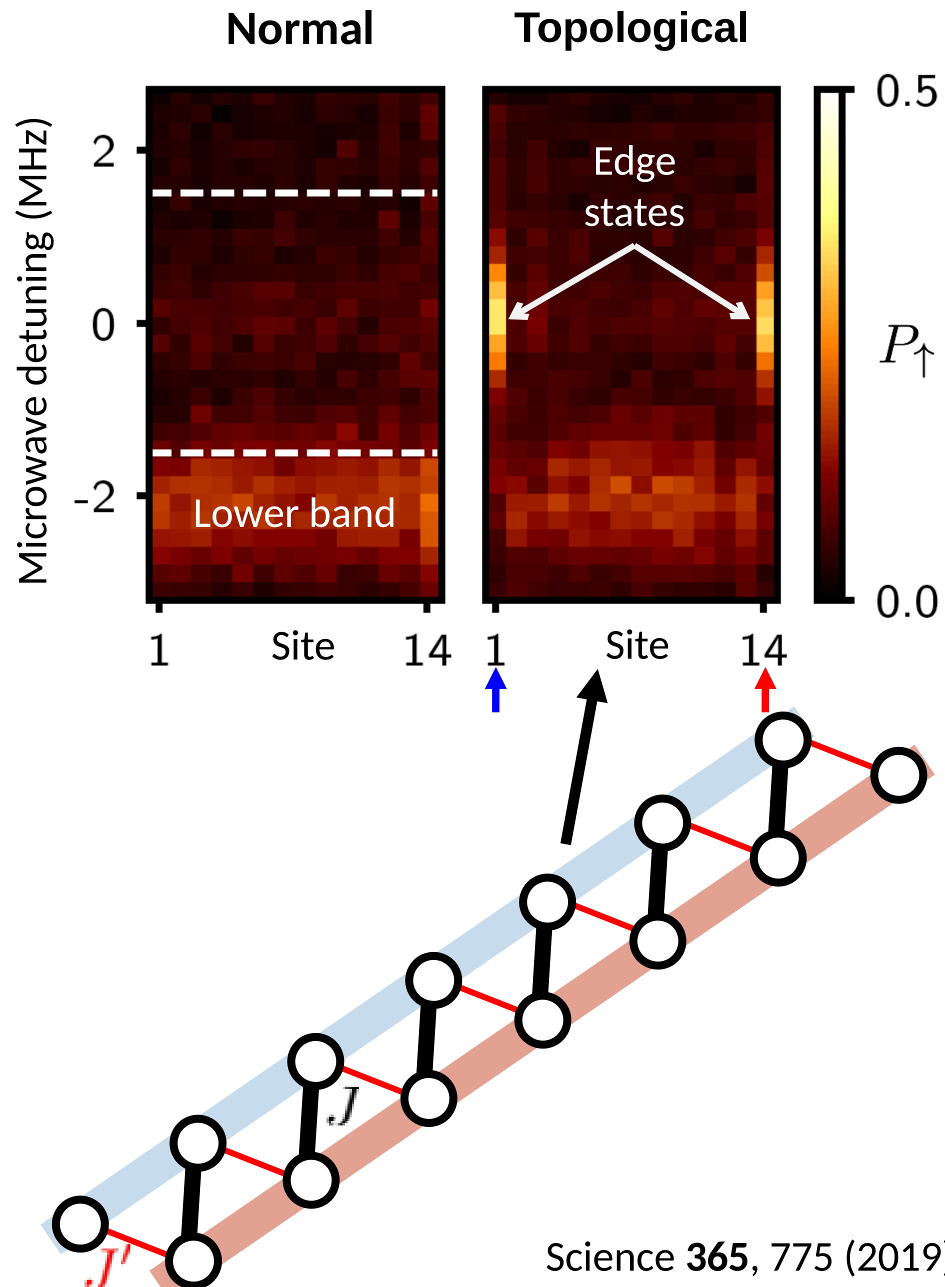

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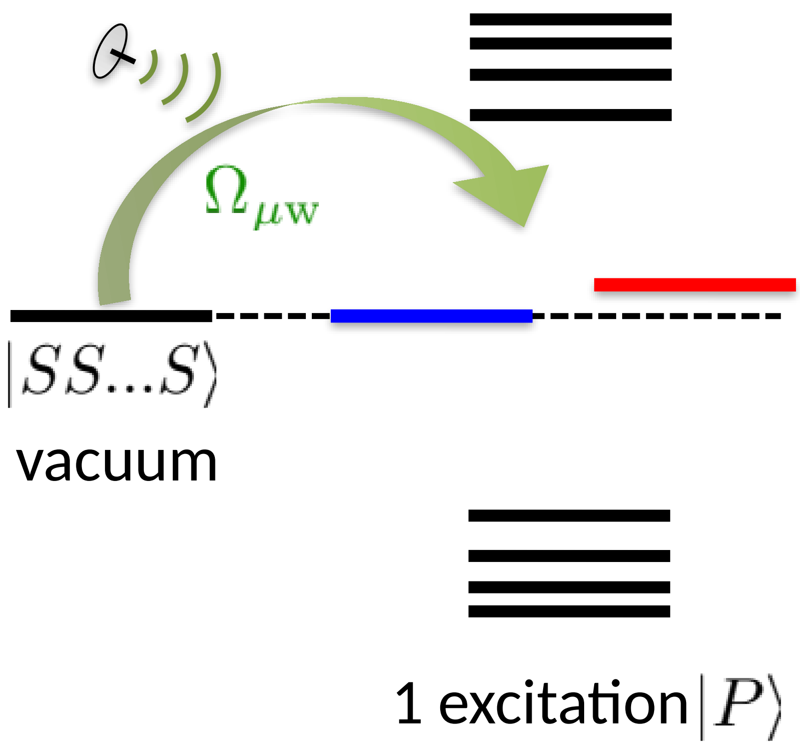

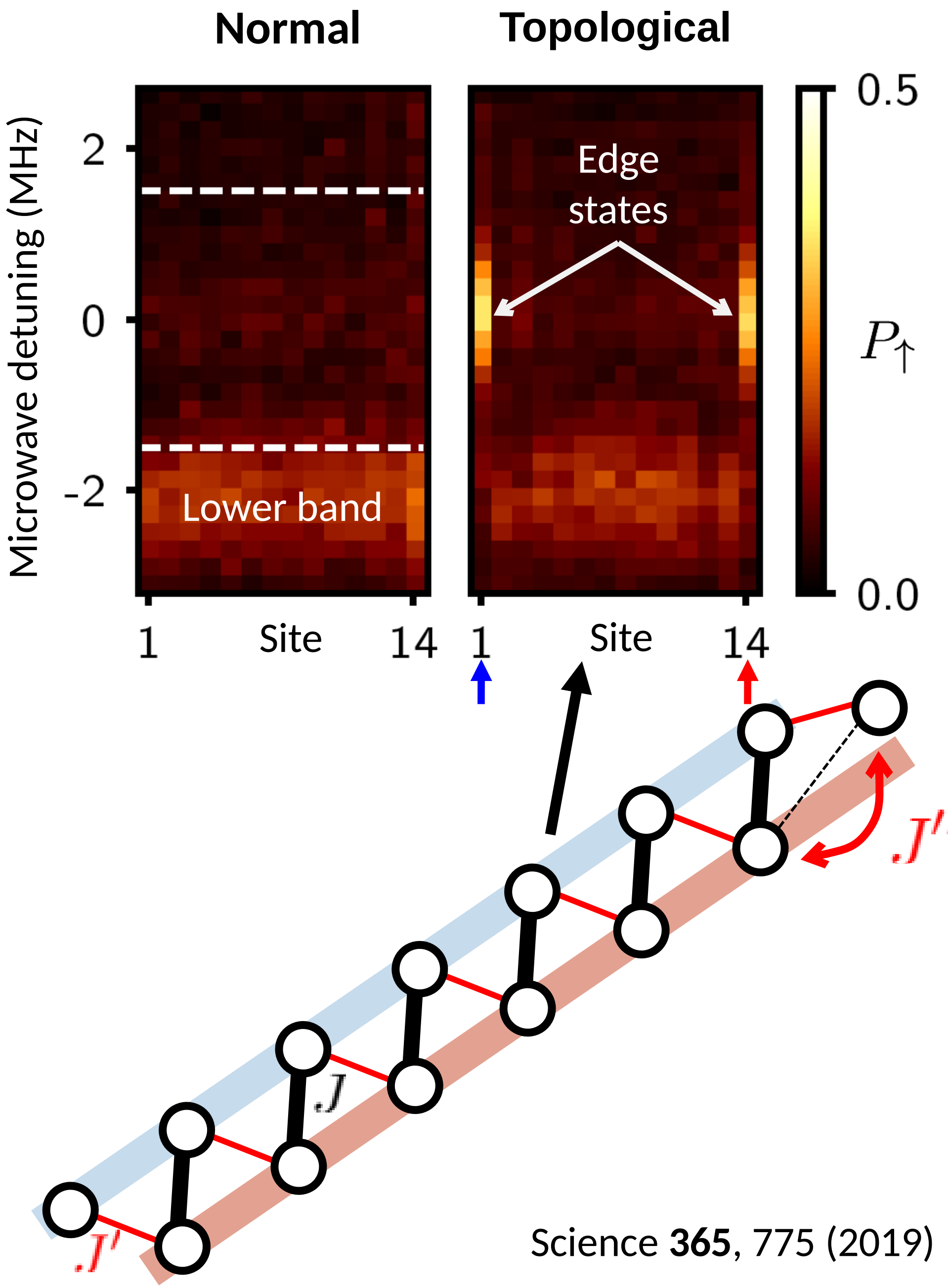

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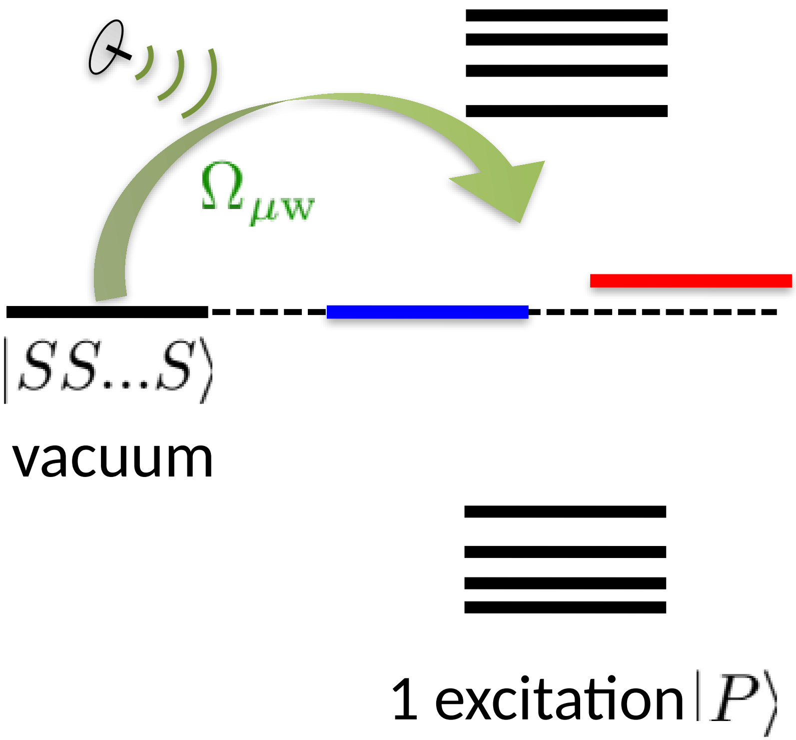
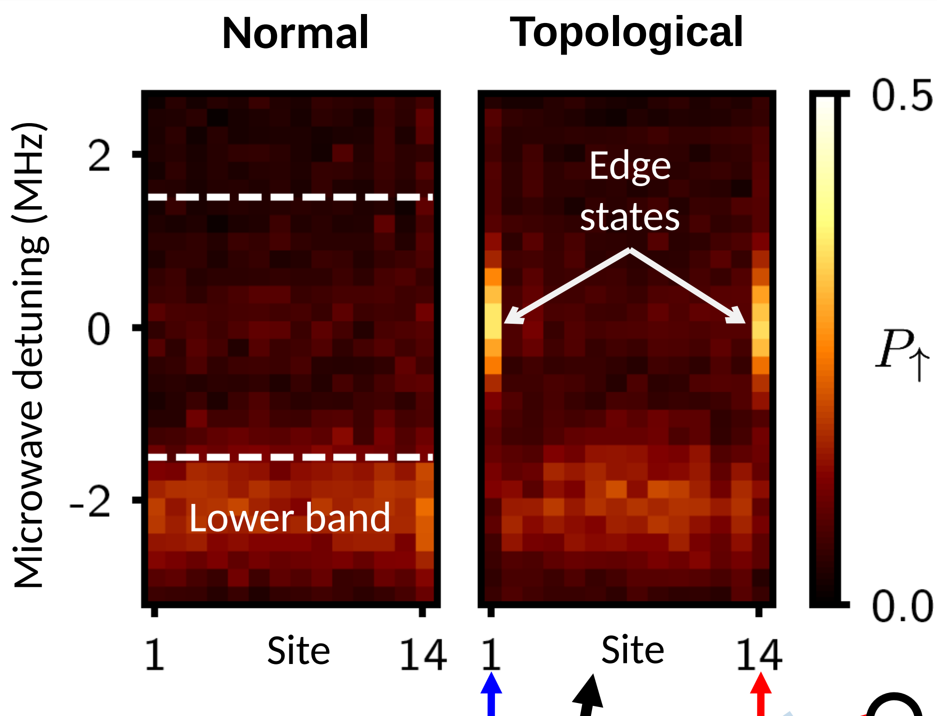
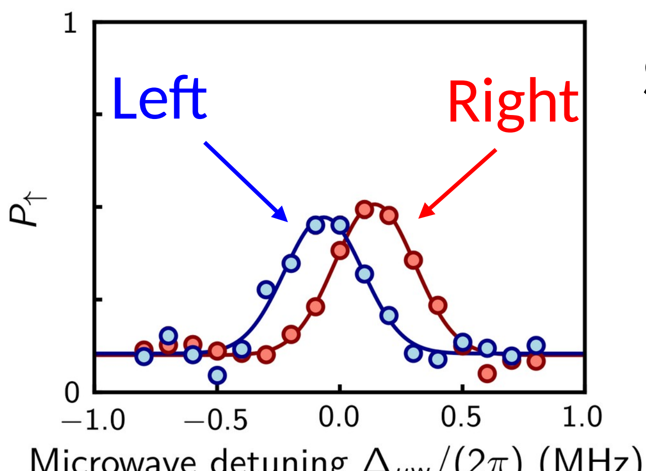
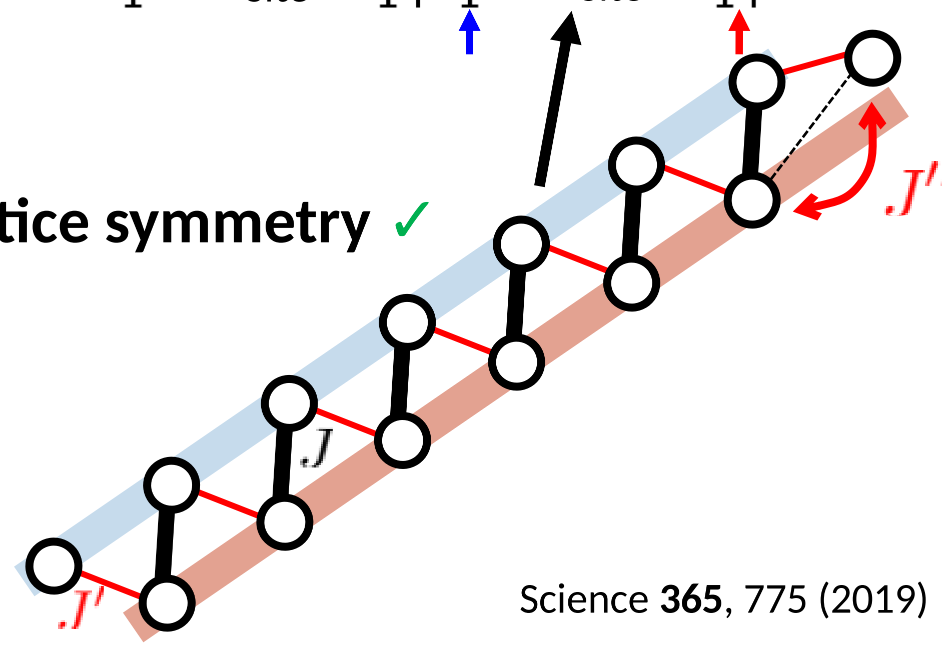






Sub-lattice symmetry ✓



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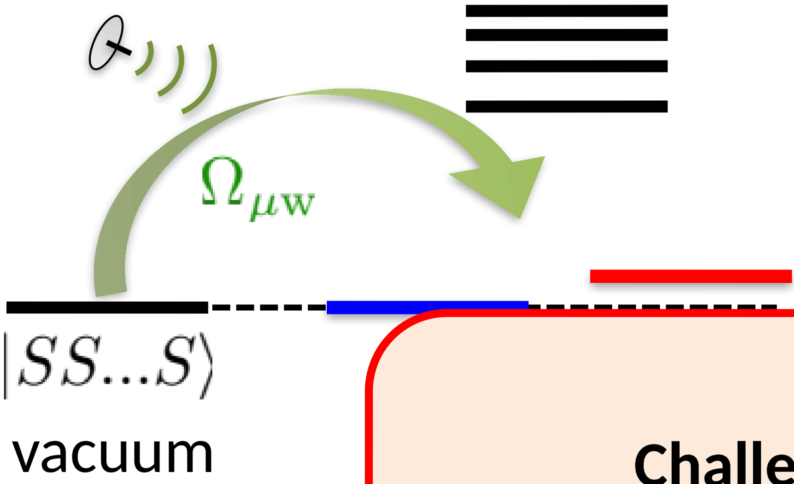
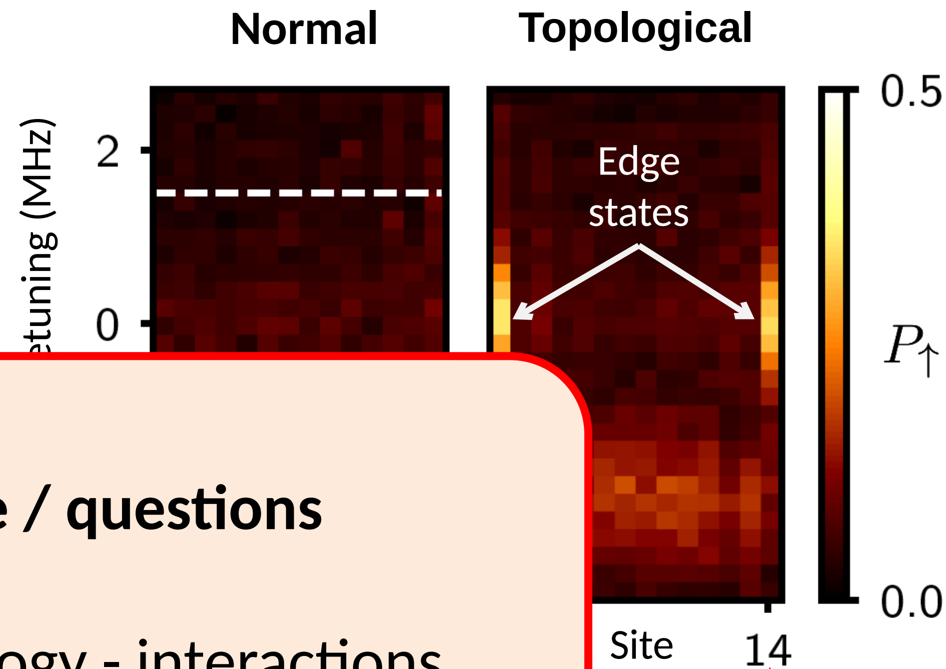
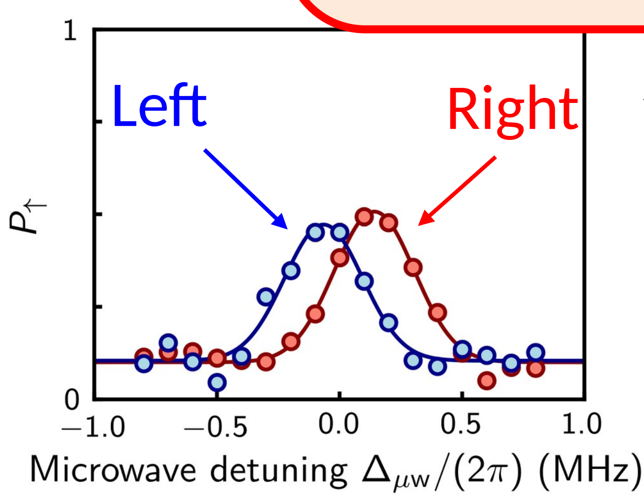




Challenge / questions

interplay topology - interactions



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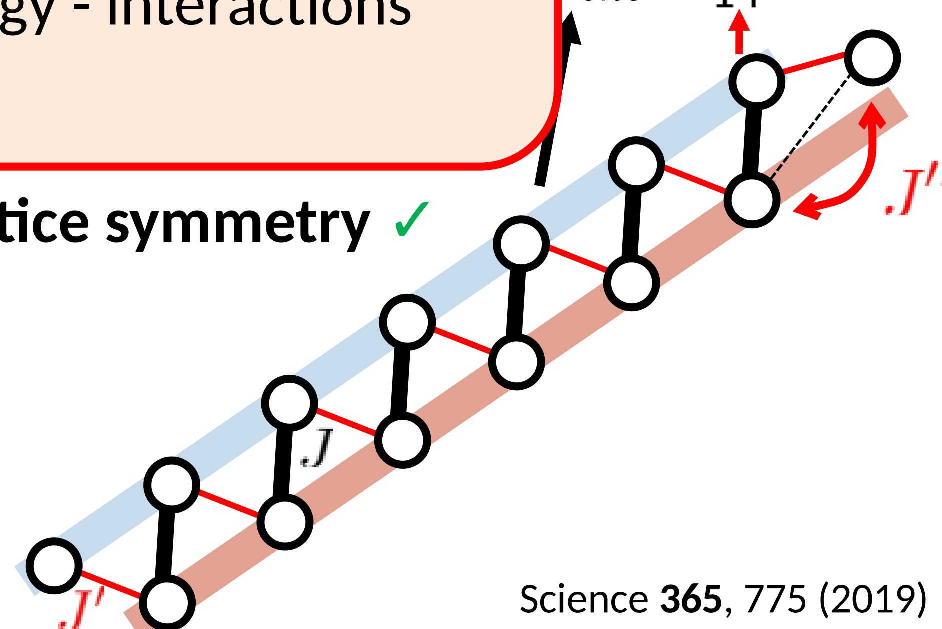
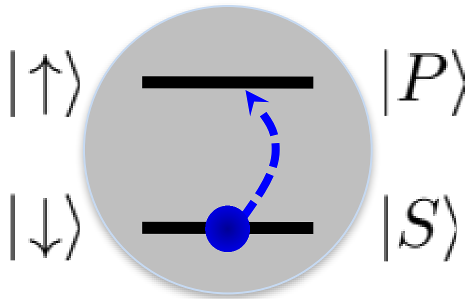


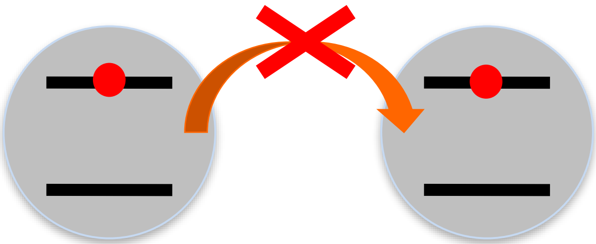
Science **365**, 775 (2019)

Realization of an interacting topological phase in 1d

Spin excitation = “particle”



Atom cannot carry 2 excitations = excitations = **hard-core bosons**



On-site interaction $U \to \infty$

$$H_{\mathrm{B}} = \sum_{i \in A, j \in B} J_{ij}(b_i^\dagger b_j + b_i b_j^\dagger), \quad b_i^{\dagger 2} = 0$$

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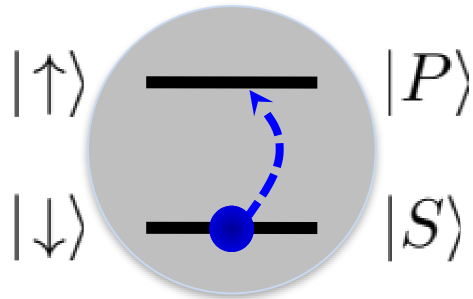

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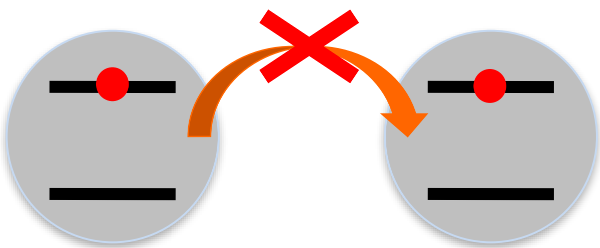

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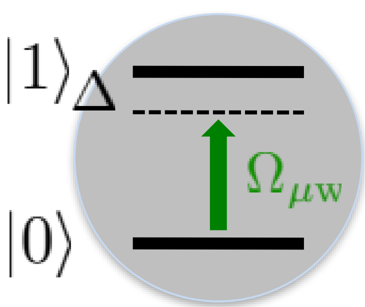
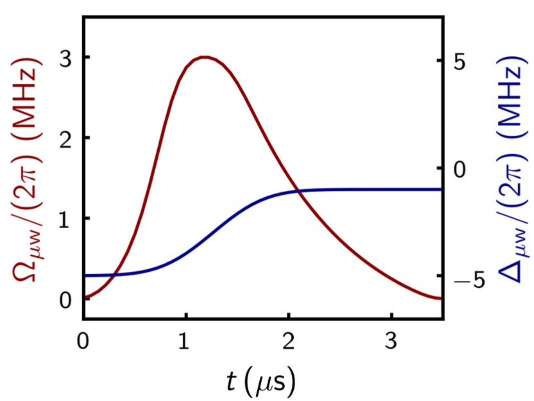
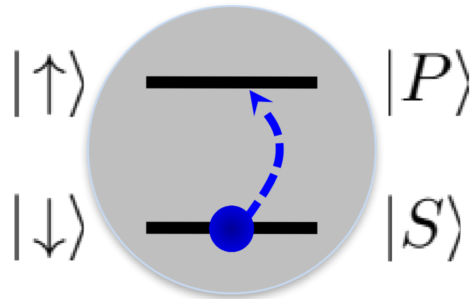
μW sweep ⇒ add excitations 1 by 1 ⇒ ground state of interacting SSH





Realization of an interacting topological phase in 1d

Spin excitation = "particle"



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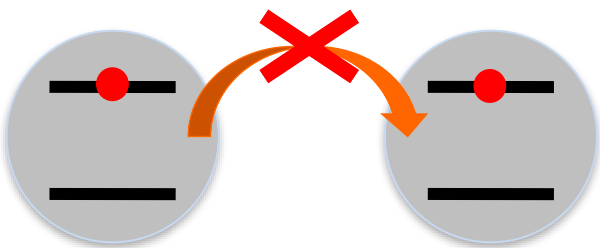

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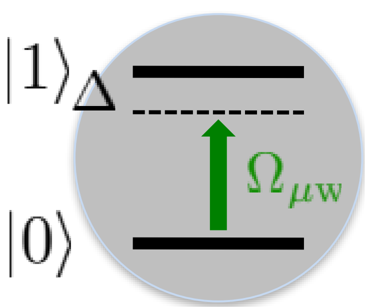

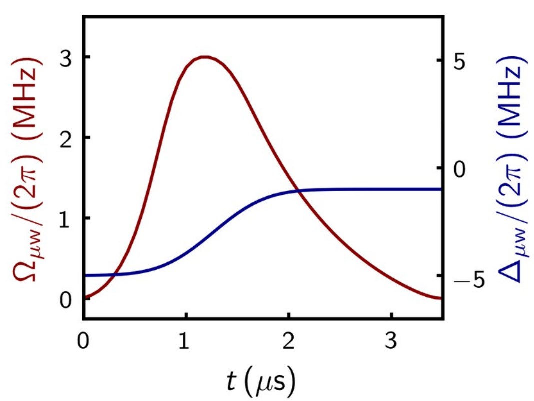

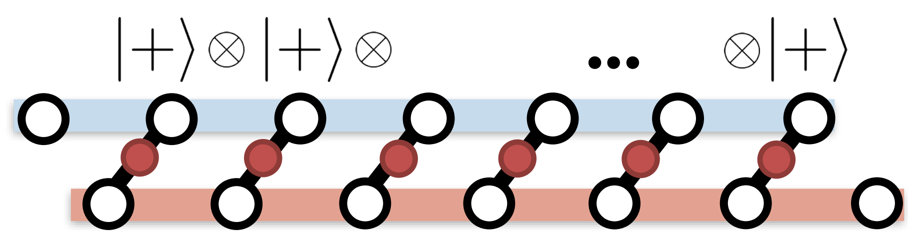

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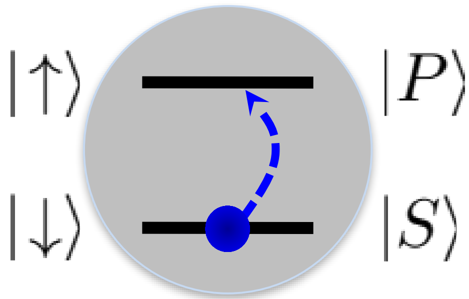

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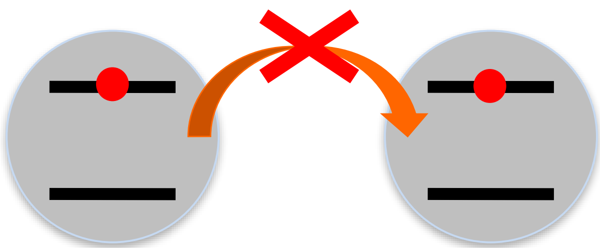

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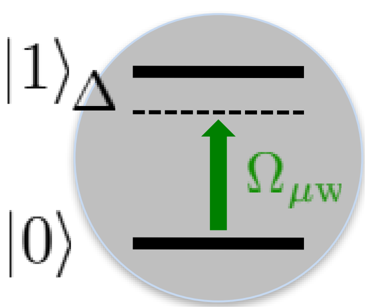
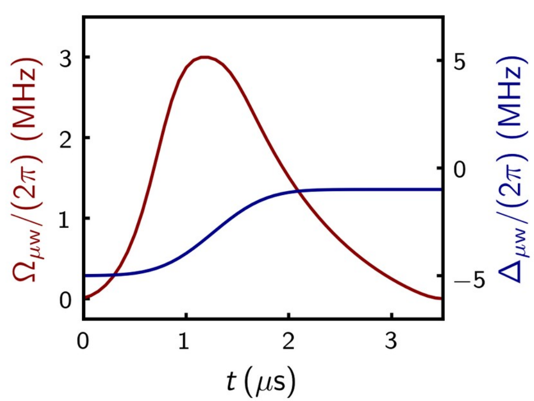
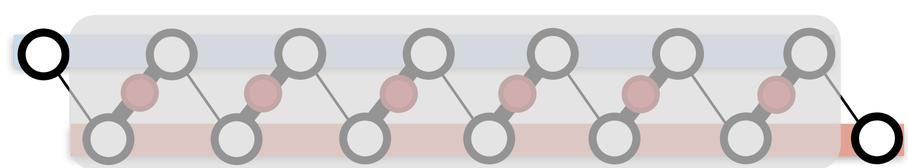
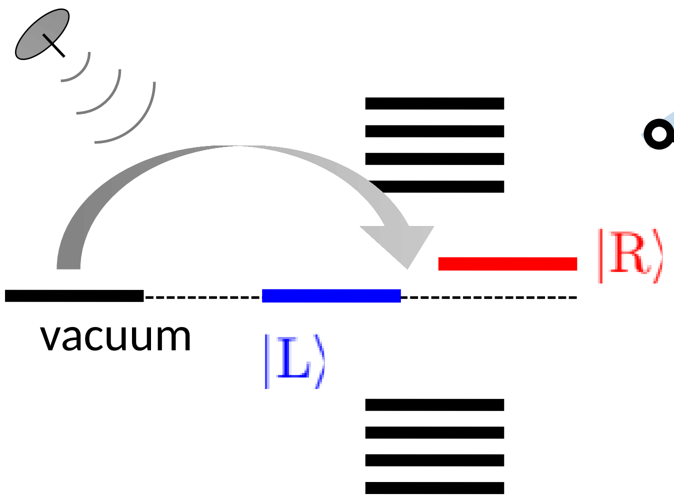


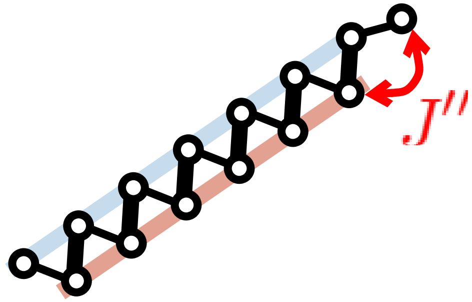


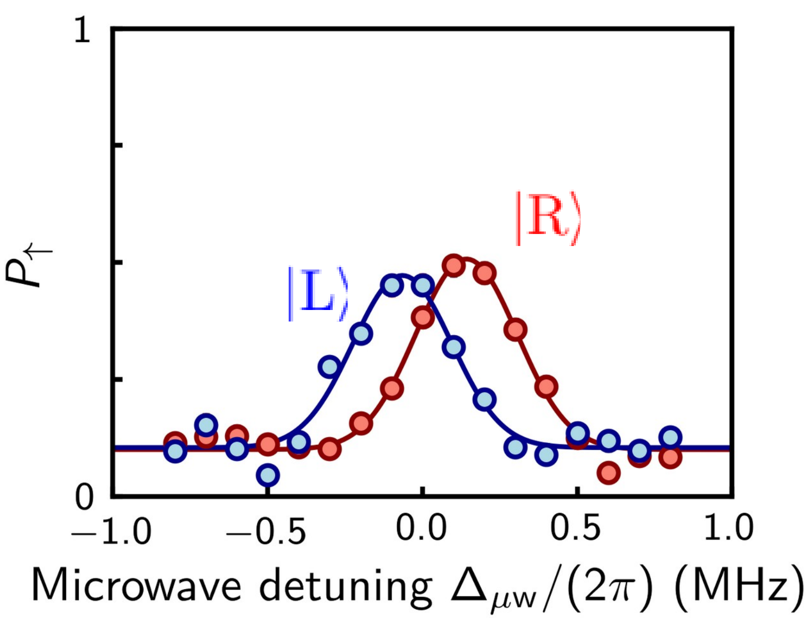
Correlated ½ - filled bulk



Single-particle







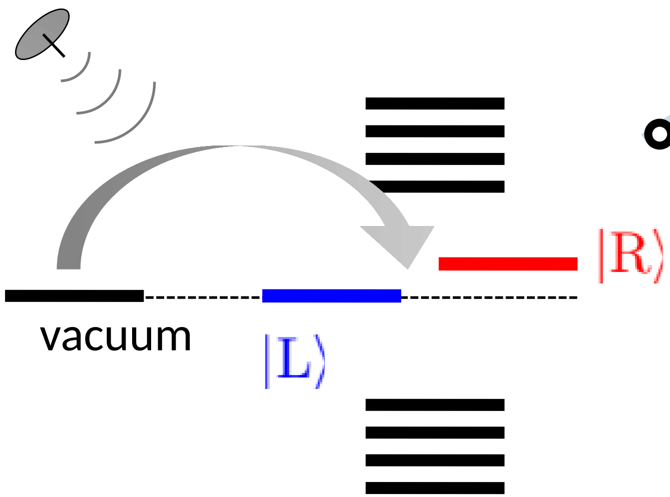
Single-particle case

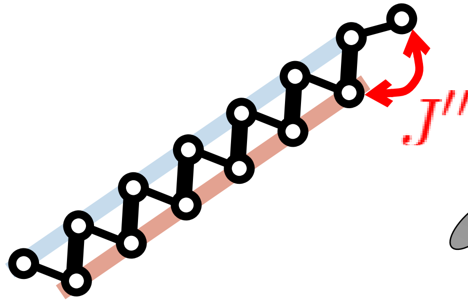
Broken chiral symmetry

= lifts degeneracy

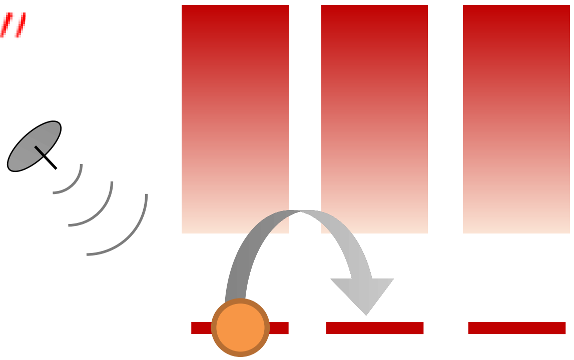
Robustess of the many-body ground state / symmetry

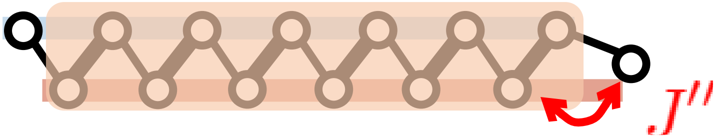
Single-particle

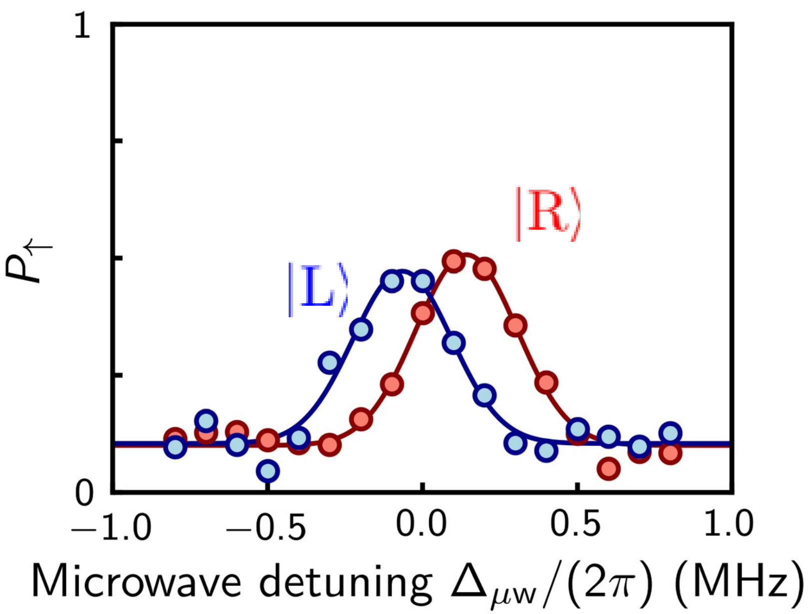




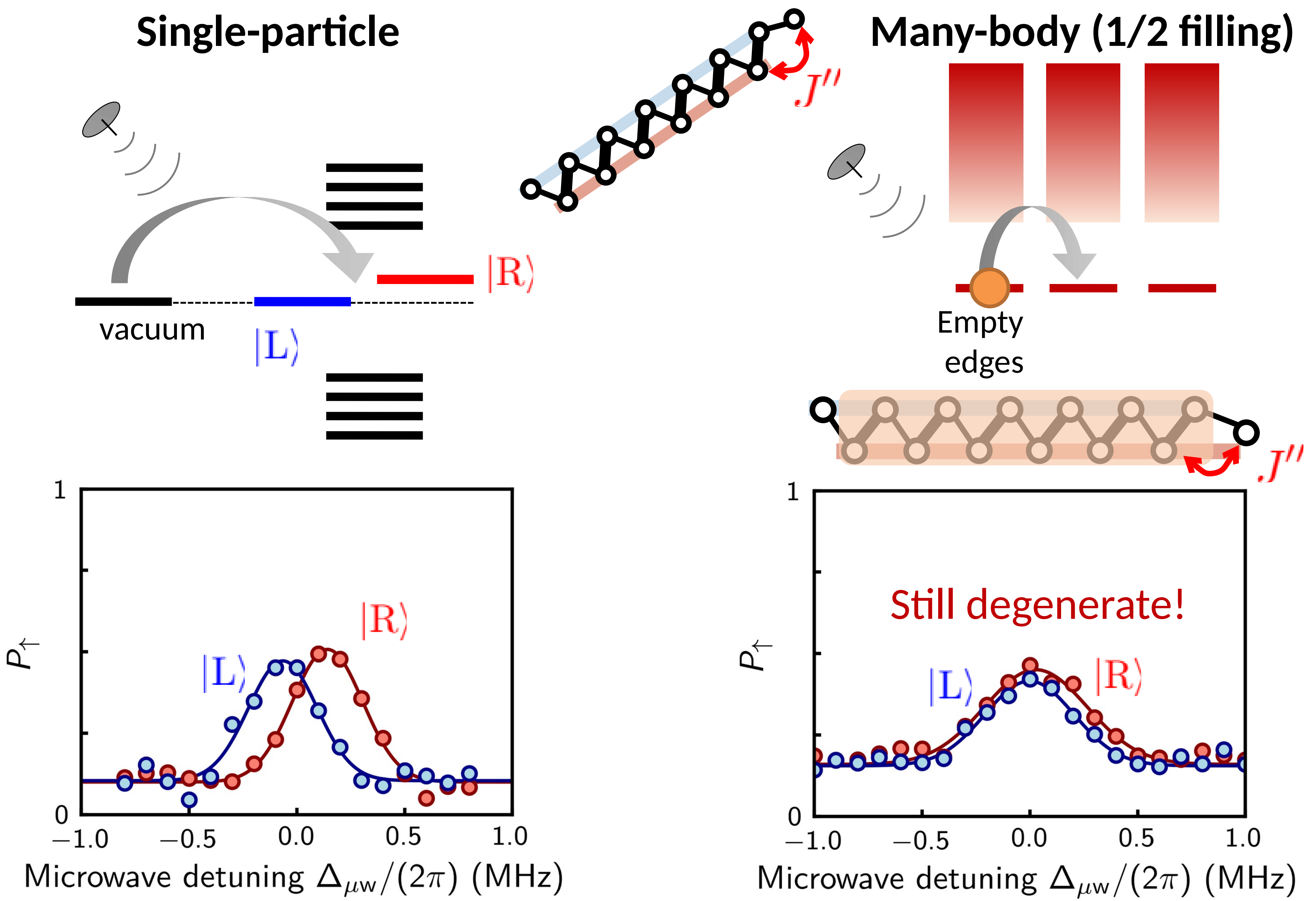
Many-body (1/2 filling)



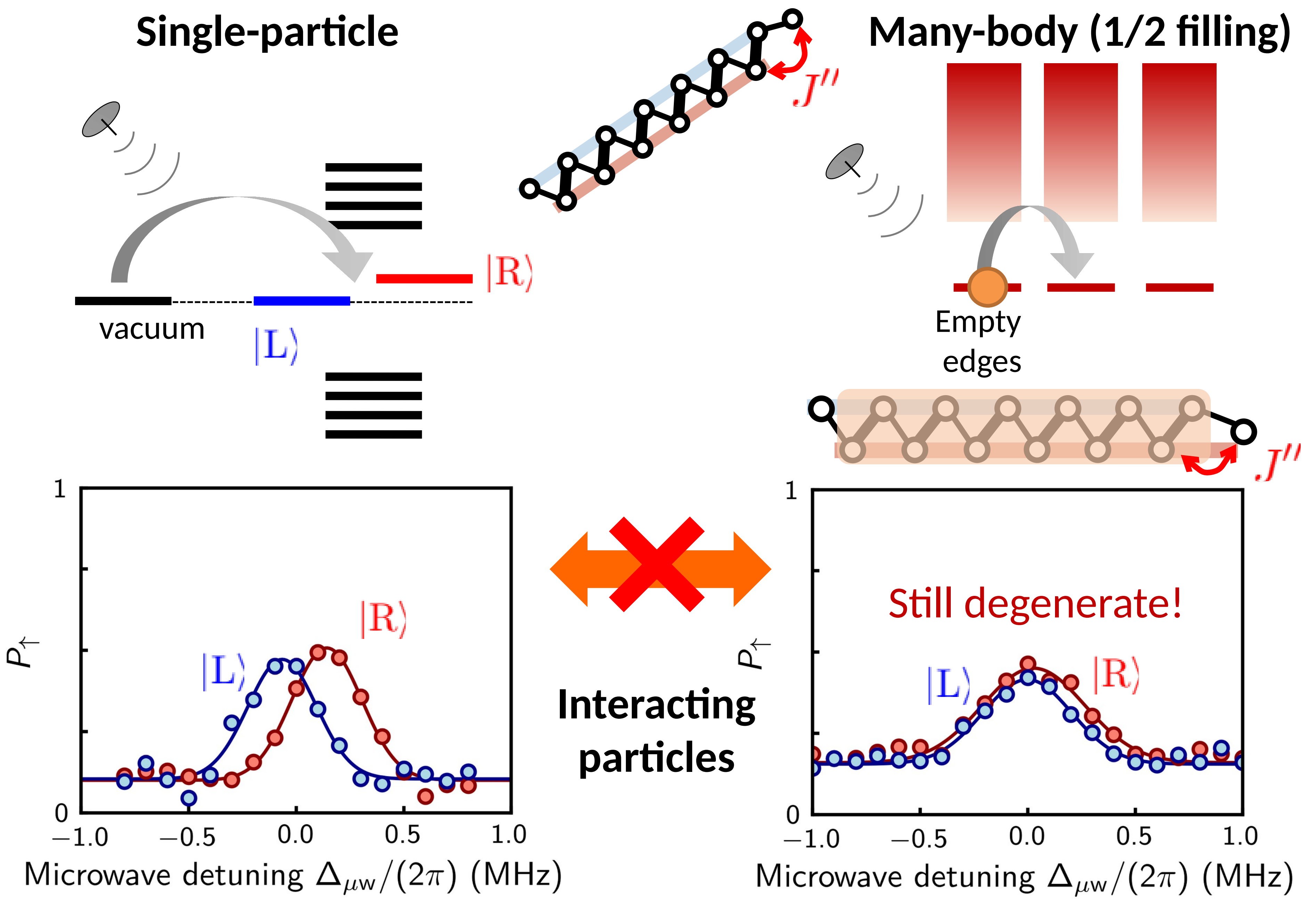




Robustess of the many-body ground state / symmetry

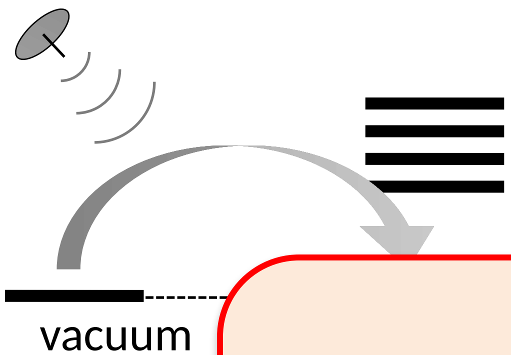


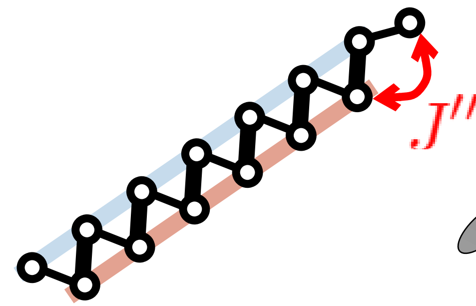
Robustess of the many-body ground state / symmetry



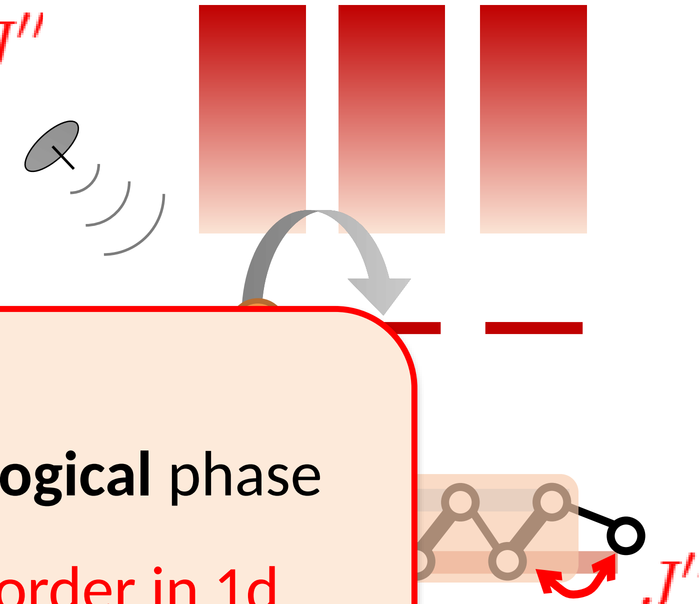
Robustess of the many-body ground state / symmetry

Single-particle





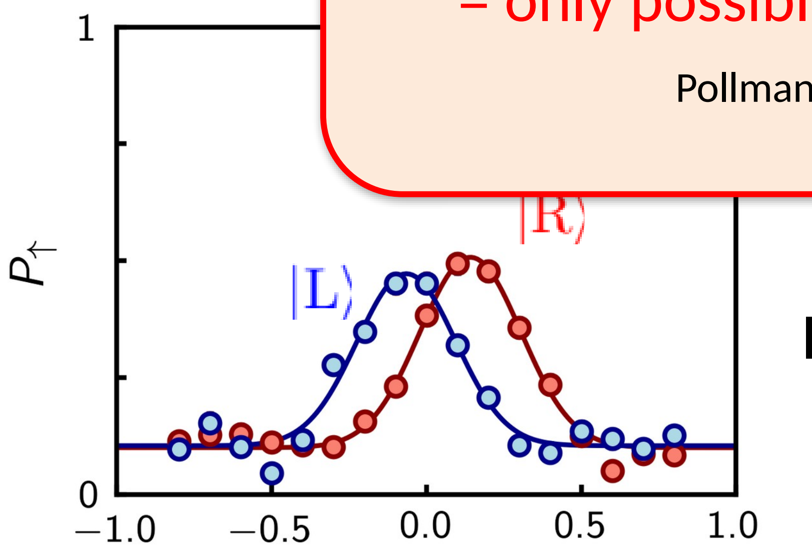
Many-body (1/2 filling)



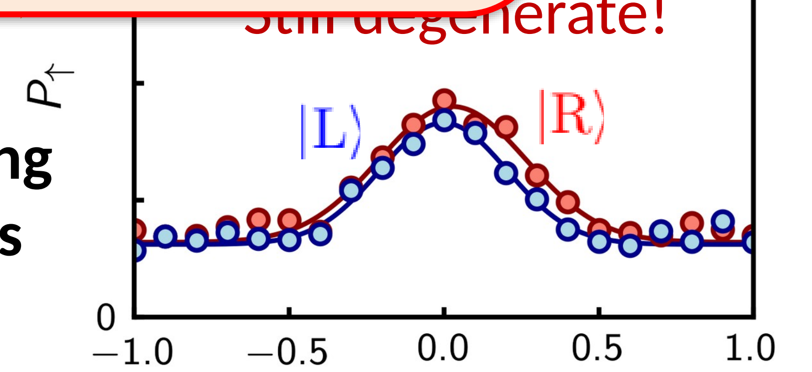
A **symmetry protected topological** phase

= only possible topological order in 1d

Pollman, PRB **85**, 075125 (2012)



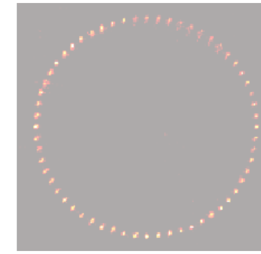
Interacting particles



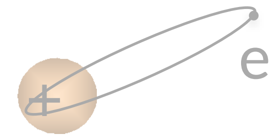
Questions?

Outline

1. **Arrays of individual atoms**



2. **Rydberg atoms and their interactions**



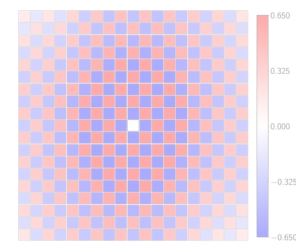
3. **Examples of quantum simulations**

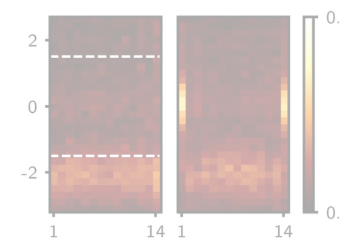
   A. Exploration of phase diagrams

   B. Out-of-Equilibrium dynamics

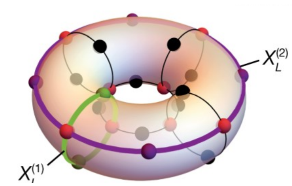
   C. Ground state preparation & squeezing

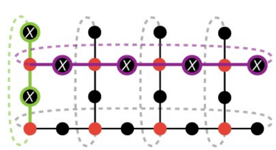
   D. Synthetic Topological matter





4. **Digital quantum computing**





Digital quantum computing: First proposals

VOLUME 85, NUMBER 10 PHYSICAL REVIEW LETTERS 4 SEPTEMBER 2000

Fast Quantum Gates for Neutral Atoms

D. Jaksch, J.I. Cirac, and P. Zoller
Institut für Theoretische Physik, Universität Innsbruck, Technikerstrasse 25, A-6020 Innsbruck, Austria

S.L. Rolston
National Institute of Standards and Technology, Gaithersburg, Maryland 20899

R. Côté[1] and M.D. Lukin[2]

VOLUME 87, NUMBER 3 PHYSICAL REVIEW LETTERS 16 JULY 2001

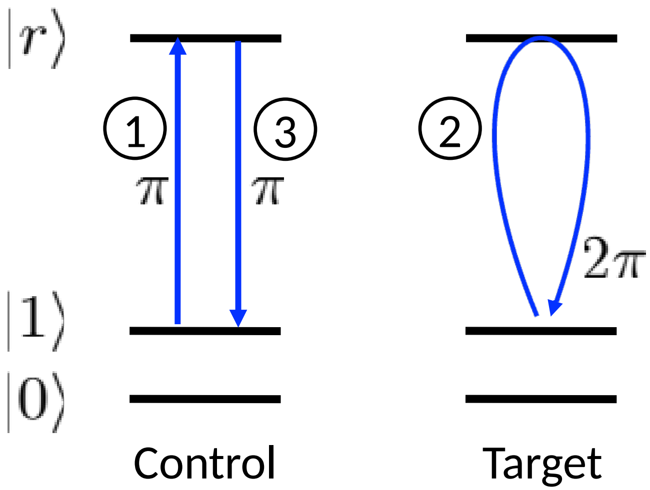
Dipole Blockade and Quantum Information Processing in Mesoscopic Atomic Ensembles

M. D. Lukin,[1] M. Fleischhauer,[1,2] and R. Cote[3]
[1]*ITAMP, Harvard-Smithsonian Center for Astrophysics, Cambridge, Massachusetts 02138*
[2]*Fachbereich Physik, Universität Kaiserslautern, D-67663 Kaiserslautern, Germany*
[3]*Physics Department, University of Connecticut, Storrs, Connecticut 06269*

L. M. Duan, D. Jaksch, J. I. Cirac, and P. Zoller
Institut für Theoretische Physik, Universität Innsbruck, A-6020 Innsbruck, Austria
(Received 7 November 2000; published 26 June 2001)

Digital quantum computing: Rydberg gates

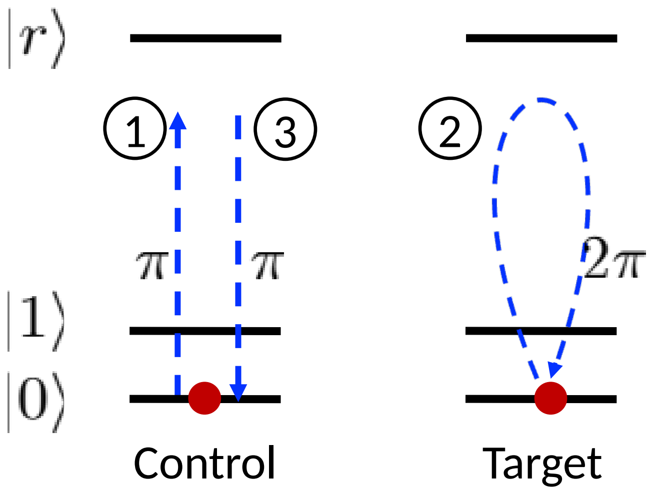
Two-qubit gates



D. Jaksch *et al.*, PRL **85**, 2208 (2000)

Saffman *et al.*, Rev. Mod. Phys. **82**, 2313 (2010)

Two-qubit gates



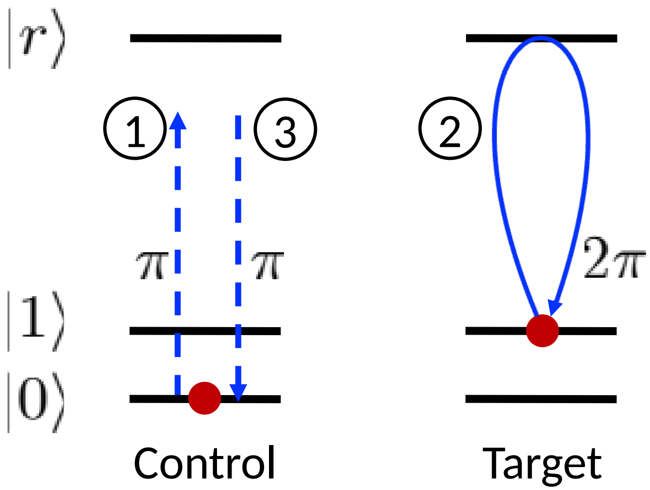
Input ① ② ③ Output

C_z operation: 00 00 00 00

D. Jaksch *et al.*, PRL **85**, 2208 (2000)

Saffman *et al.*, Rev. Mod. Phys. **82**, 2313 (2010)

Two-qubit gates



Input ① ② ③ Output

C_z operation:

00 → 00 → 00 → 00

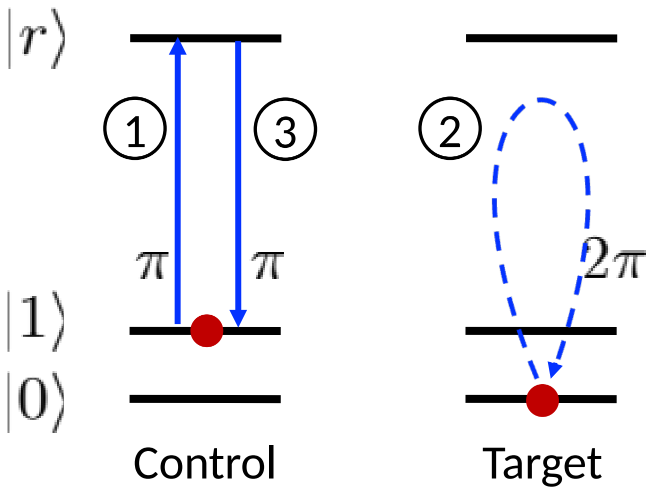
01 → 01 → -01 → -01

D. Jaksch *et al.*, PRL **85**, 2208 (2000)

Saffman *et al.*, Rev. Mod. Phys. **82**, 2313 (2010)

Digital quantum computing: Rydberg gates

Two-qubit gates



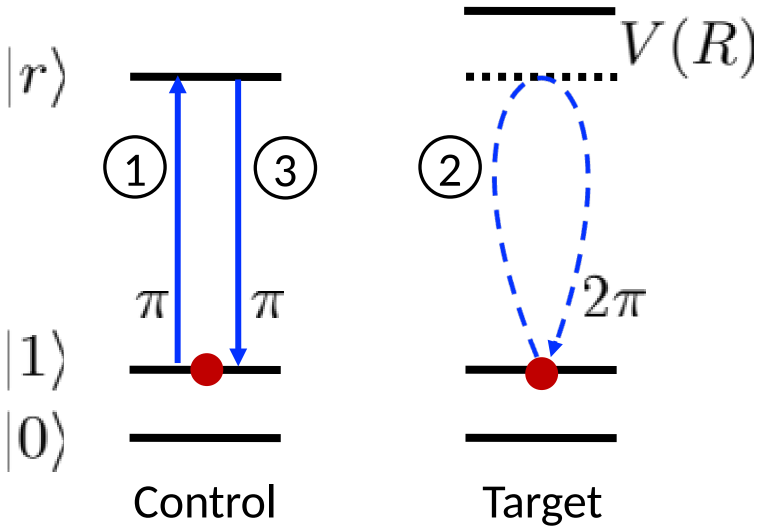
C_z operation:

Input		①		②		③ Output		
00	⬭	00	⬭	00			⬭	00
01	⬭	01	⬭	-01	⬭	-01		
10	⬭	r0	⬭	r0			⬭	-10

D. Jaksch *et al.*, PRL **85**, 2208 (2000)

Saffman *et al.*, Rev. Mod. Phys. **82**, 2313 (2010)

Two-qubit gates



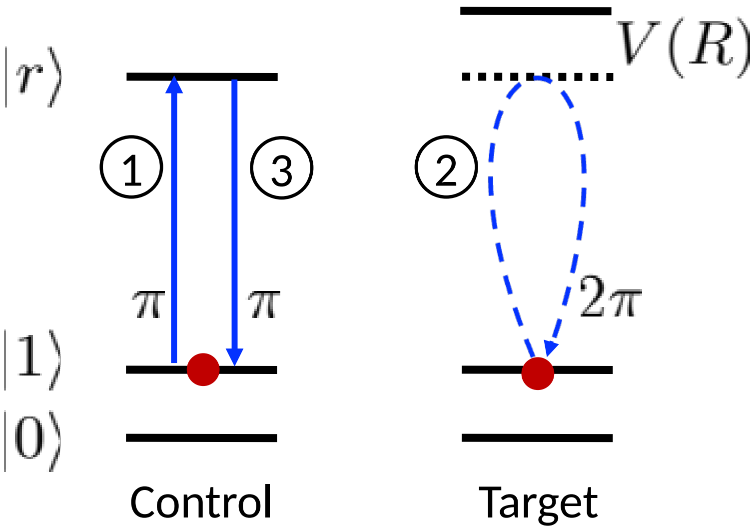
C_z operation:

Input	①	②	③	Output
00	00	00		00
01	01	-01		-01
10	r0	r0		-10
11	r1	r1		-11

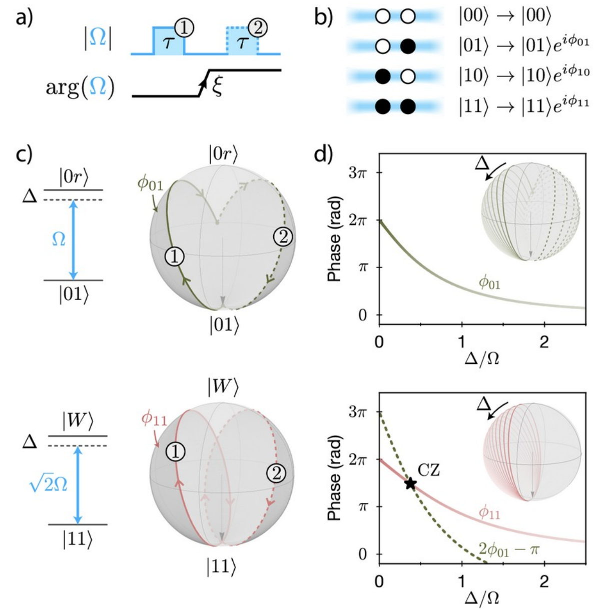
Blockade

D. Jaksch *et al.*, PRL **85**, 2208 (2000)
Saffman *et al.*, Rev. Mod. Phys. **82**, 2313 (2010)

Digital quantum computing: Rydberg gates



Levine –Pichler gate



	Input	①	②	③ Output
C_z operation:	00	00	00	00
	01	01	-01	-01
	10	r0	r0	-10
	11	r1	r1	-11

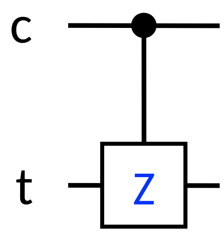
Blockade

D. Jaksch *et al.*, PRL **85**, 2208 (2000)

Saffman *et al.*, Rev. Mod. Phys. **82**, 2313 (2010)

From C_Z to CNOT

The CNOT gate can be obtained with the controlled-phase C_Z and single qubit rotations (Hadamard)



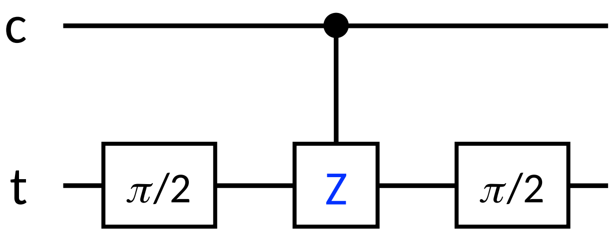
C_Z

$$\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$$

D. Jaksch *et al.*, PRL **85**, 2208 (2000)
Saffman *et al.*, Rev. Mod. Phys. **82**, 2313 (2010)

From C_Z to CNOT

The CNOT gate can be obtained with the controlled-phase C_Z and single qubit rotations (Hadamard)



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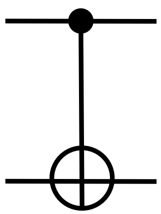


CNOT

$$\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{pmatrix}$$

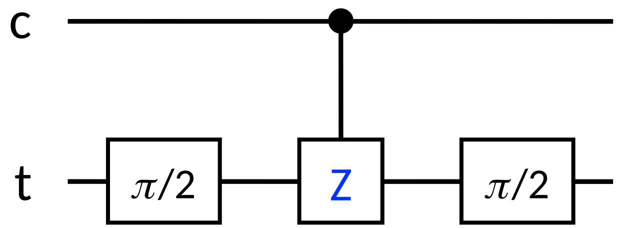
C_Z

$$\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$$

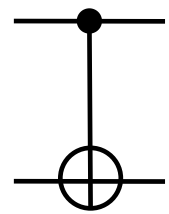
D. Jaksch *et al.*, PRL **85**, 2208 (2000)

Saffman *et al.*, Rev. Mod. Phys. **82**, 2313 (2010)

The CNOT gate can be obtained with the controlled-phase C_Z and single qubit rotations (Hadamard)



¿



CNOT

$$\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{pmatrix}$$

CNOT Operation

Input		Output
00	→	00
01	→	01
10	→	11
11	→	10

CNOT can be used to prepare entanglement

Bell state

00 → (0+1)0 = 00 + 10 → 00 + 11

Rotate c-qubit

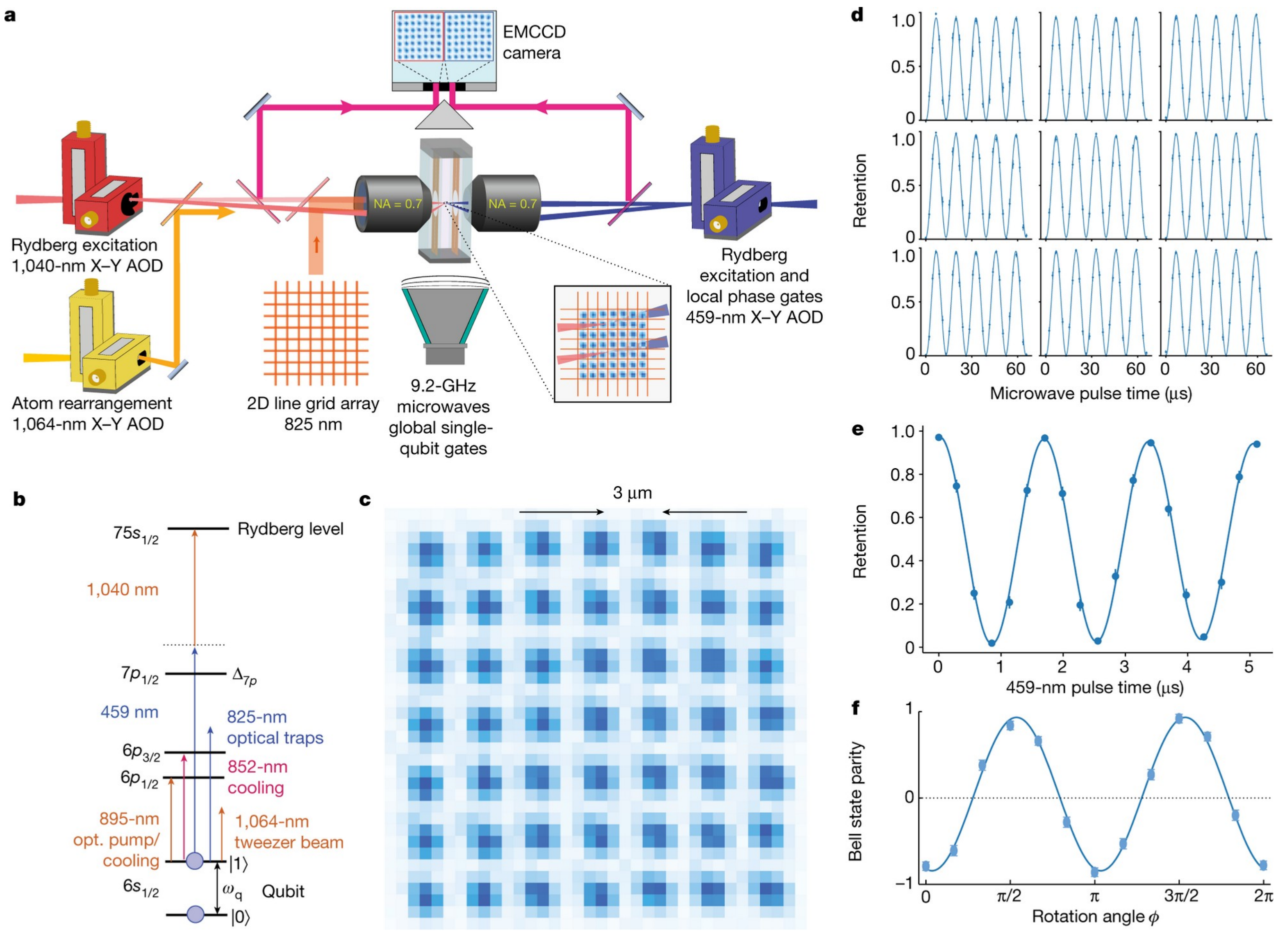
CNOT

D. Jaksch *et al.*, PRL **85**, 2208 (2000)

Saffman *et al.*, Rev. Mod. Phys. **82**, 2313 (2010)

Digital quantum computing in arrays

Cs



Digital circuits applied to:

- Quantum phase estimation

  14 C_Z gates

- MaxCut problem

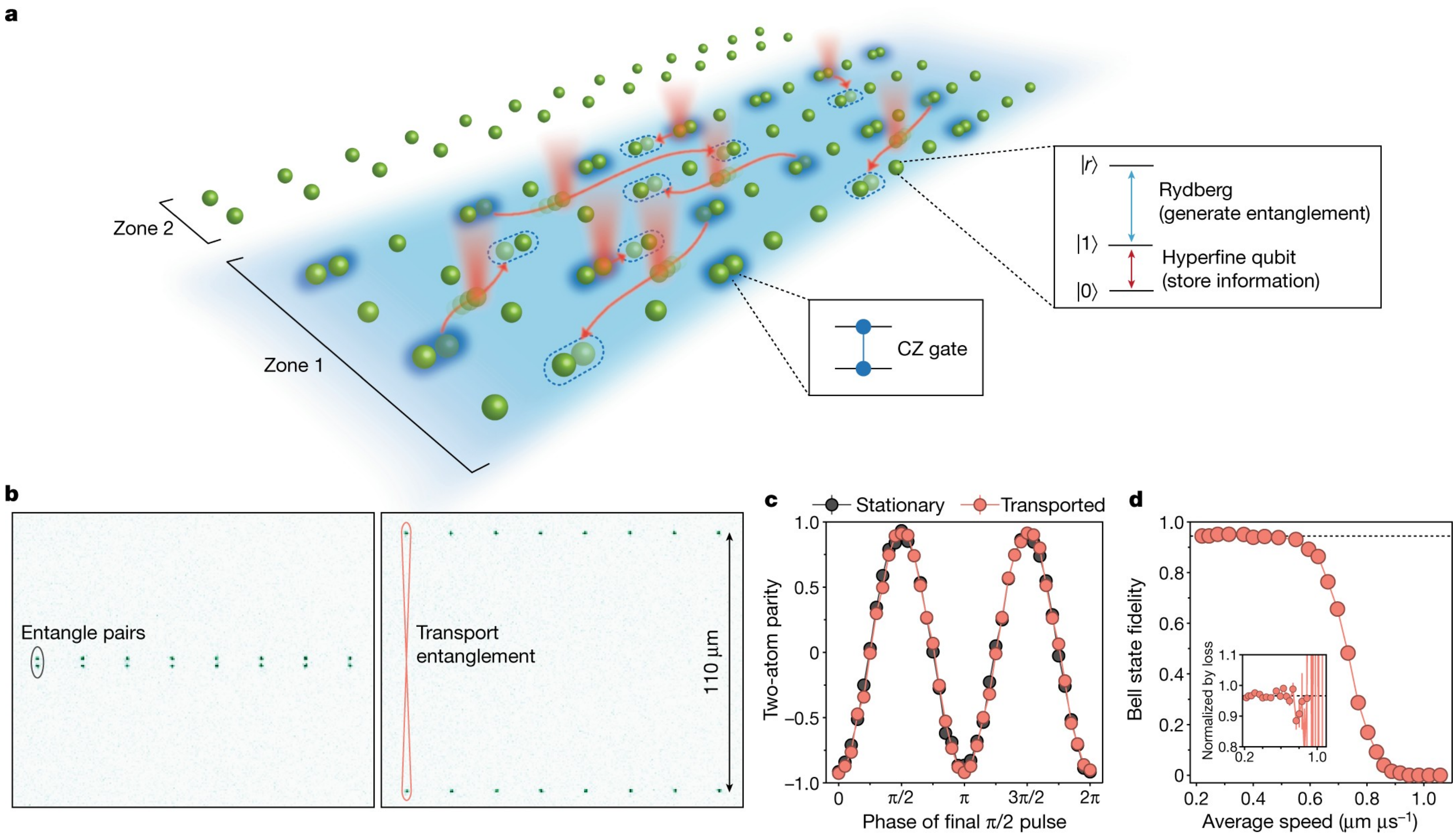
  43 single qubit gates,
  18 C_Z gates

2Q Bell state fidelity
Raw/SPAM
0.957(0.982)

Graham *et al.*, Nature **604**, 457 (2022)

Non-local connectivity

Long distance transport enables programmable and non-local connectivity

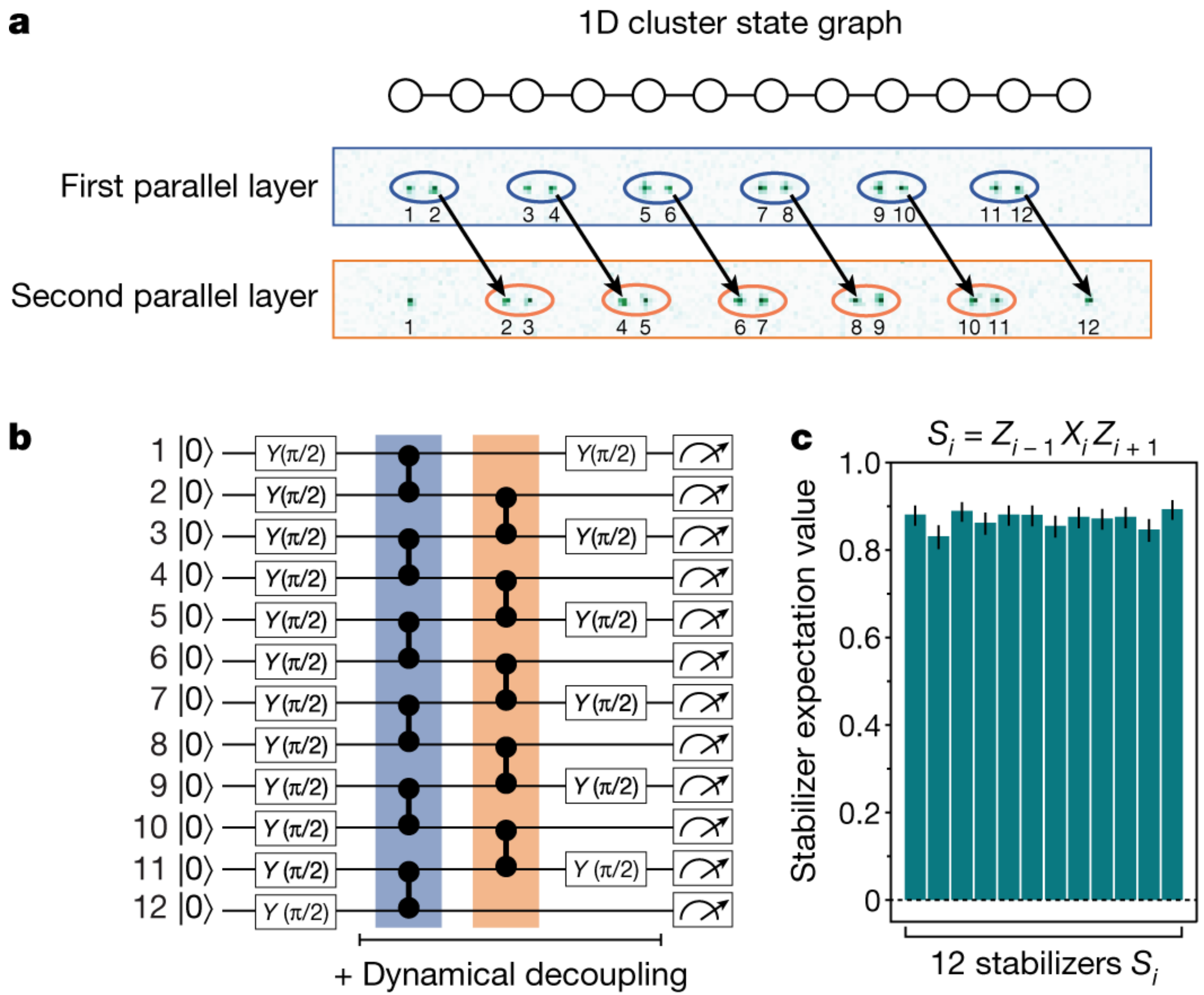


Bluvstein *et al.*, Nature **604**, 451 (2022)

Non-local connectivity & error detection

Example: Preparation of a cluster state

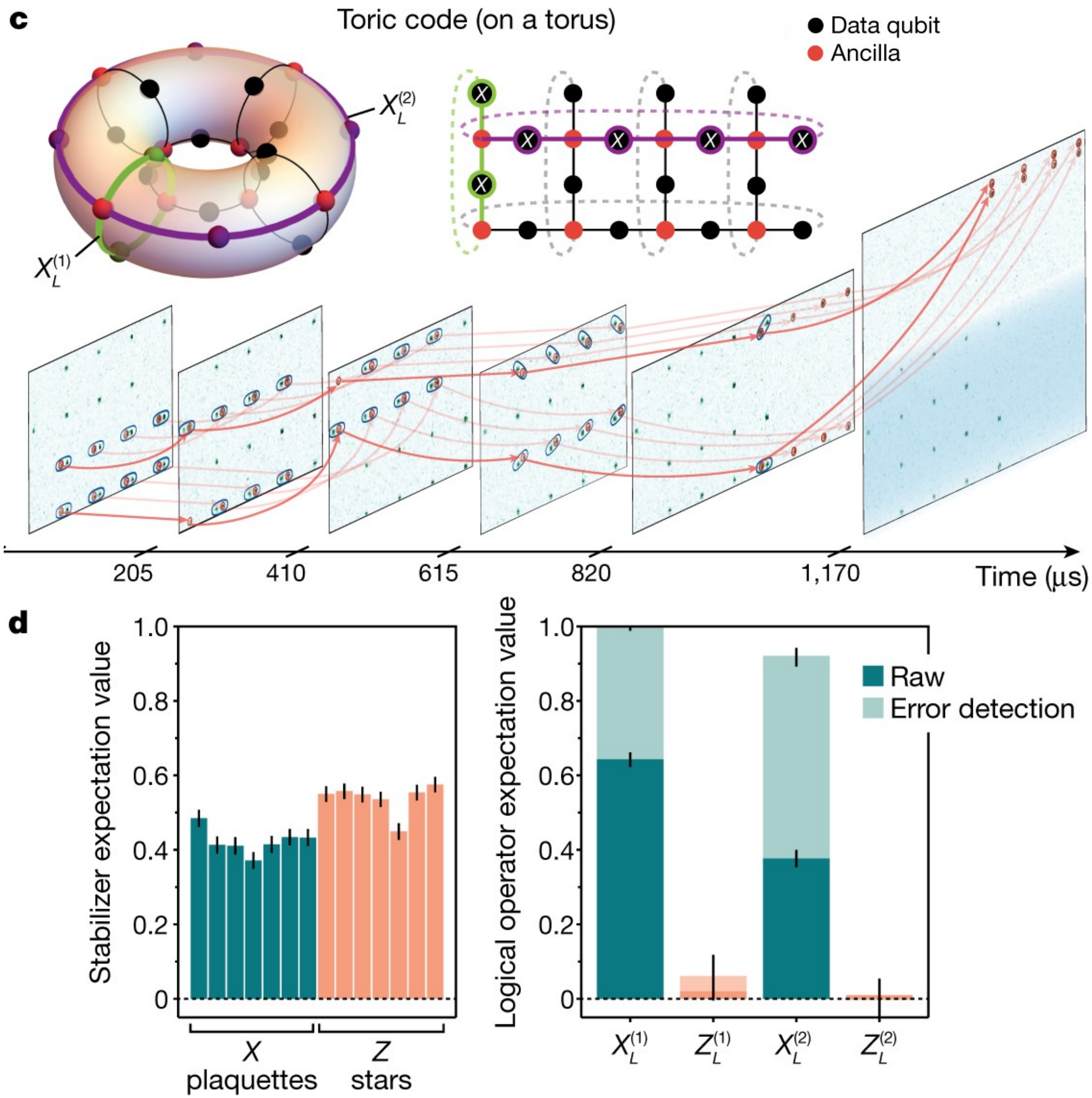
Rb



Bluvstein *et al.*, Nature **604**, 451 (2022)

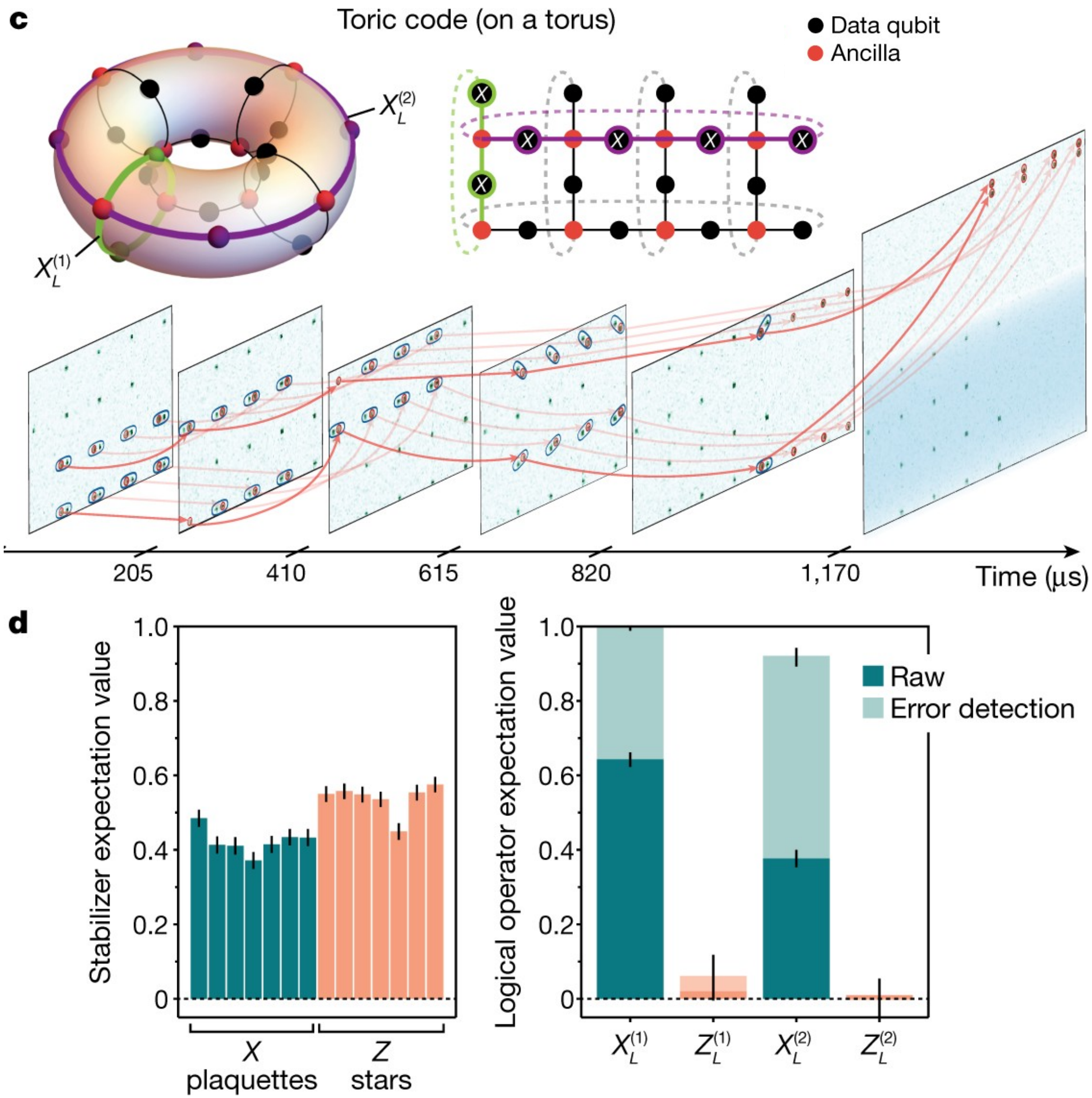
Non-local connectivity & error detection

Rb

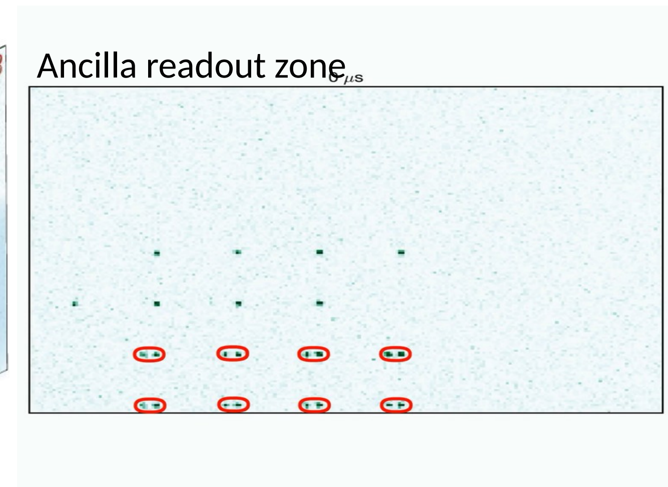


Bluvstein *et al.*, Nature **604**, 451 (2022)

Non-local connectivity & error detection

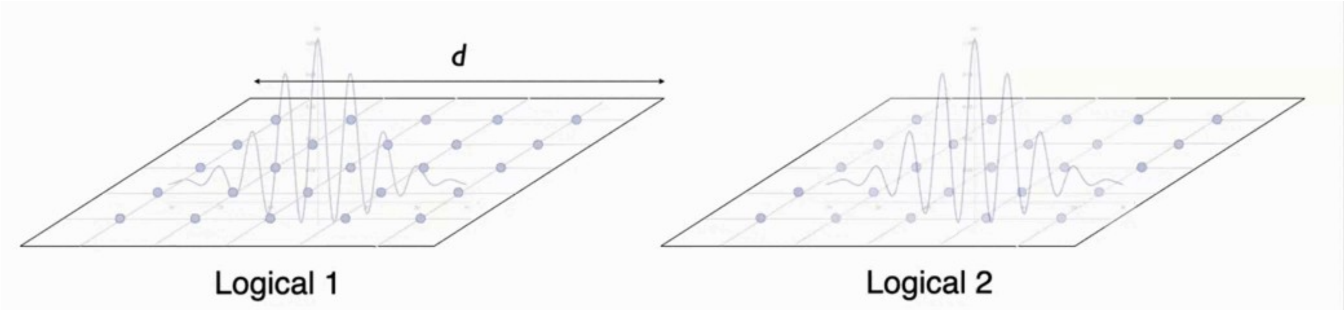


Rb

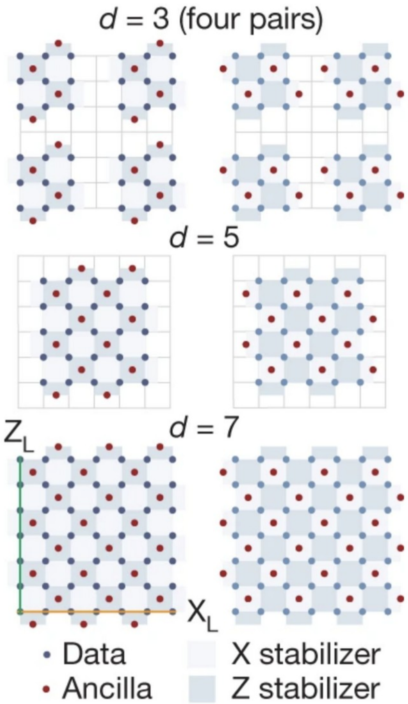


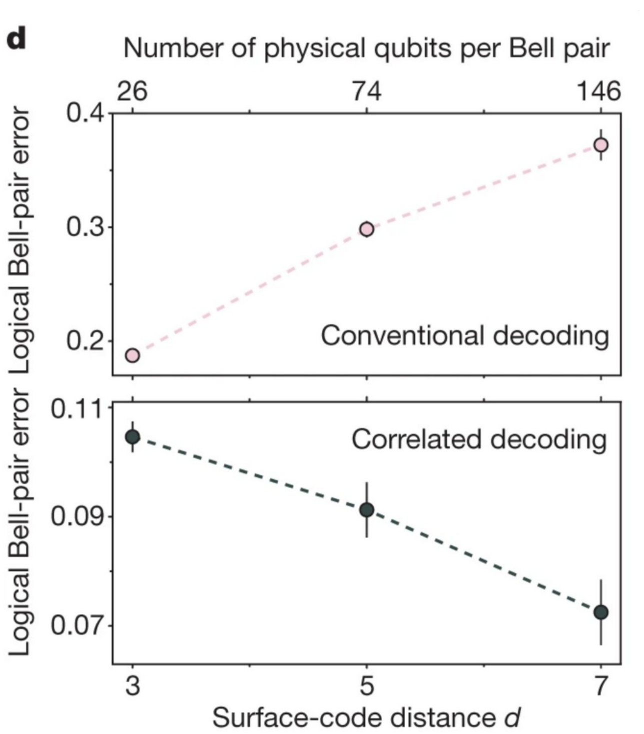
Bluvstein *et al.*, Nature **604**, 451 (2022)

Transversal CNOT with logical qubits



Logical CNOT with surface correction





Errors decrease with surface-code distance!

Hallmark of quantum error correction

Bluvstein, Nature **626**, 58 (2024)

A logical quantum processor in operation

7-dimensional hypercube circuit (48 logical qubit algorithm)

Entangling zone

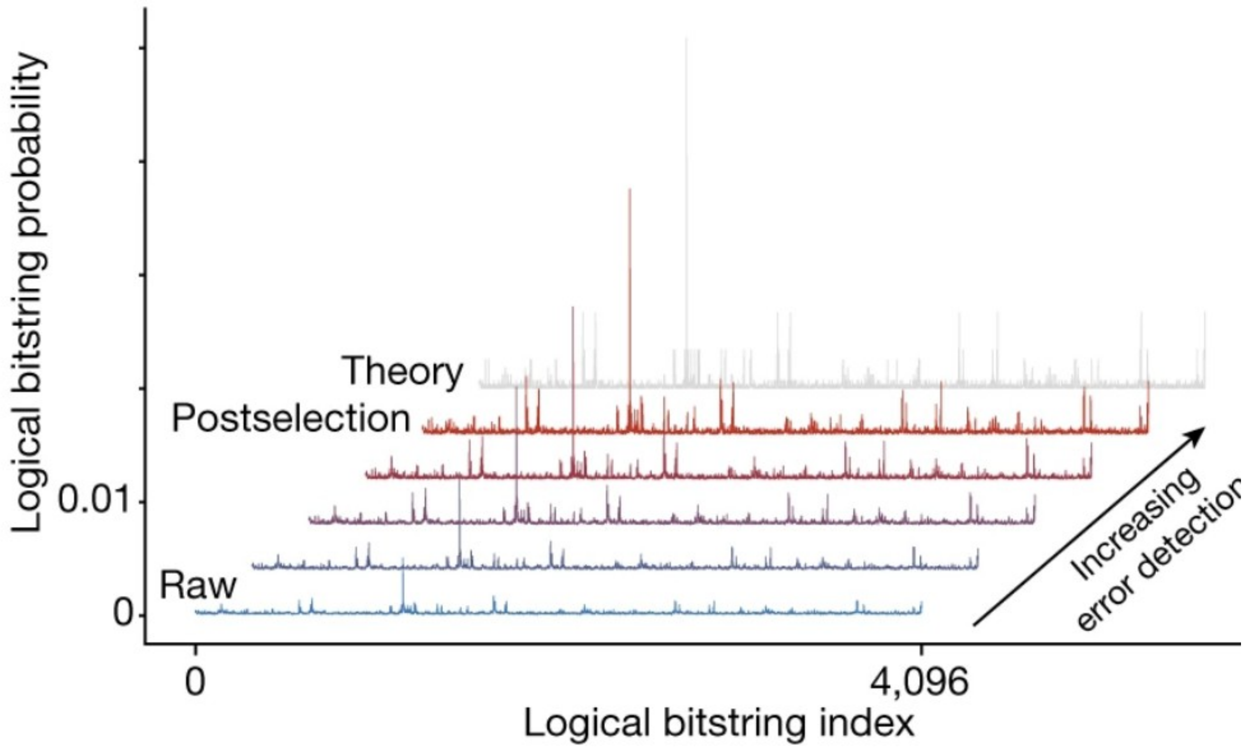
Storage zone

Bluvstein, Nature **626**, 58 (2024)

quera.link/QEC1

A logical quantum processor based on atomic arrays

Sampling complex circuits

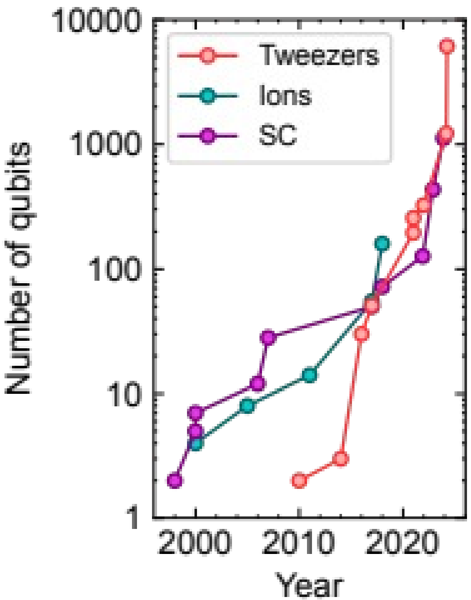


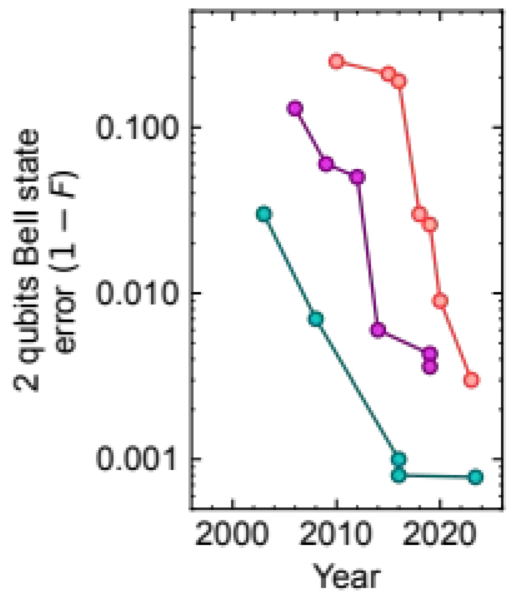
Up to 48 logical qubit circuits, 3D codes, non-Clifford operations, mid-circuit readout…

Bluvstein, Nature **626**, 58 (2024)

Evolution of the neutral atom platform

Neutral atoms vs other platforms





New startup companies

PASQAL — Massy, France

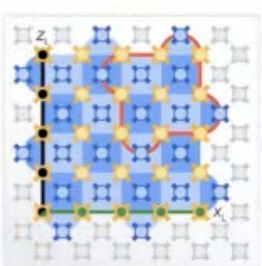
planqc — Munich, Germany

M SQUARED LASERS — Glasgow, UK

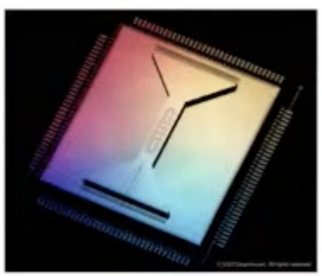
QuEra Computing Inc. — Boston, MA USA

atom computing — Berkeley, CA USA

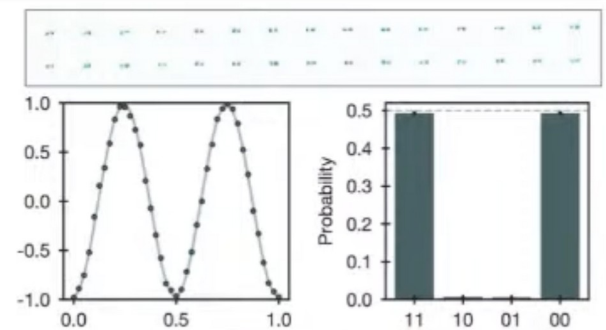
Infleqtion (ColdQuanta, SUPER.TECH) — Boulder, CO USA



Superconducting transmons (Google)
Google Quantum AI. *Nature* **614**, 676 (2023)
Average 2Q error: 0.6%



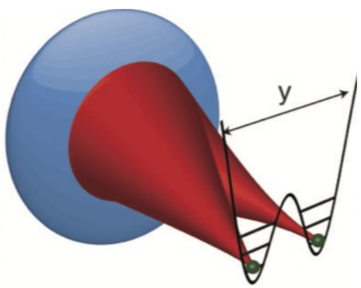
Trapped ions (Quantinuum)
S. Moses, et. al. *arXiv*:2305.03828 (2023)
Average 2Q error: 0.18%

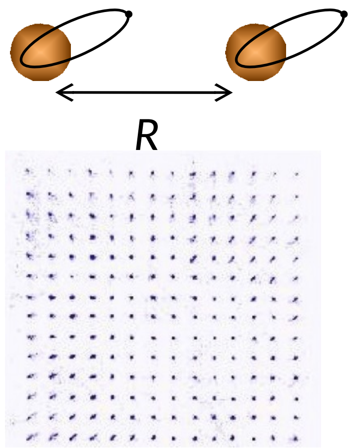


Neutral atoms (Harvard)
S. Evered, et. al. *Nature* **622**, 268 (2023)
Average 2Q error: 0.5%

Tweezer arrays: applications

Quantum simulation





Regal, Kaufman, Thomson…

Optical clocks

PHYSICAL REVIEW X 9, 041052 (2019)

Featured in Physics

An Atomic-Array Optical Clock with Single-Atom Readout

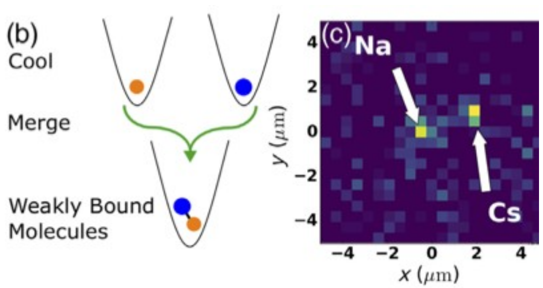
Ivaylo S. Madjarov,[1] Alexandre Cooper,[1] Adam L. Shaw,[1] Jacob P. Covey,[1] Vladimir Schkolnik,[2] Tai Hyun Yoon,[1,†] Jason R. Williams,[2] and Manuel Endres[1,*]

Half-minute-scale atomic coherence and high relative stability in a tweezer clock

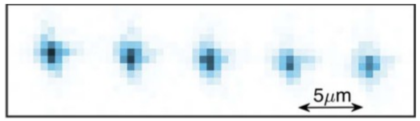
https://doi.org/10.1038/s41586-020-3009-y
Received: 18 June 2020

Aaron W. Young[1,2], William J. Eckner[1,2], William R. Milner[1,2], Dhruv Kedar[1,2], Matthew A. Norcia[1,2], Eric Oelker[1,2], Nathan Schine[1,2], Jun Ye[1,2] & Adam M. Kaufman[1,2]

Molecule engineering

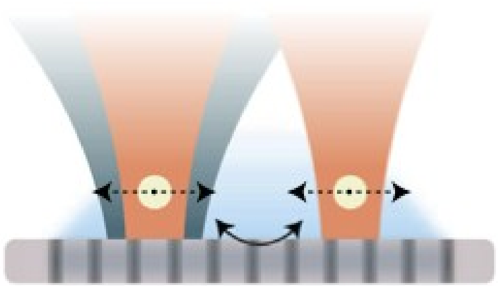


CaF



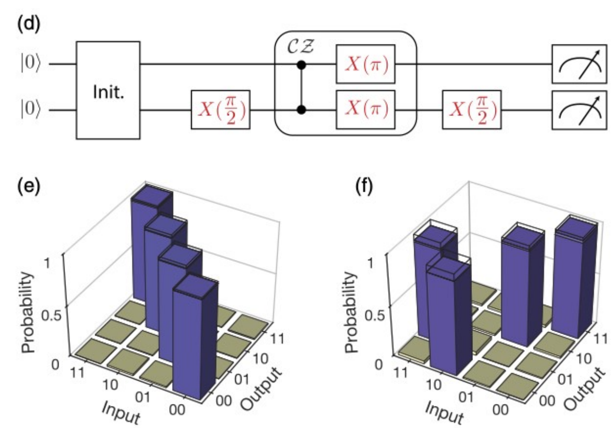
Ni, Doyle…

Tool for cQED



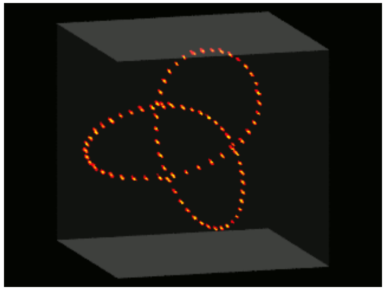
Lukin

Quantum gates



Saffman, Lukin…

Summary and outlook



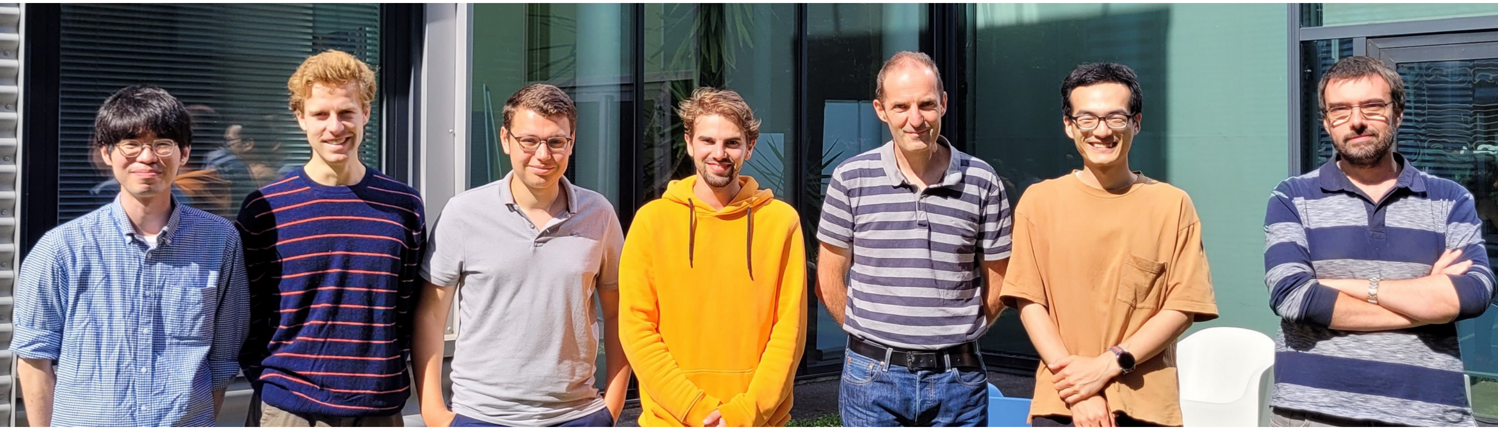
A platform to build synthetic matter

- Single-particle resolution & addressing
- Easily scalable to 1000s qubits, arbitrary geometries (2D, 3D)
- Tunable interactions = implementation of **many-body *H***

Future directions:

- Analog quantum simulation (spin liquids, LGTs)
- Applications in optimization problems (hybrid computing)
- Digital quantum computing (gate model)
- Hybrid plaftorms + optical cavities

The Rydberg team in Palaiseau



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Jamie Boyd

Lucas Leclerc

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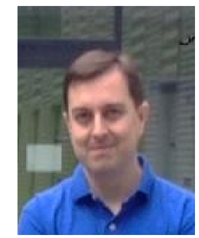

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Looking for PhDs & postdocs !!

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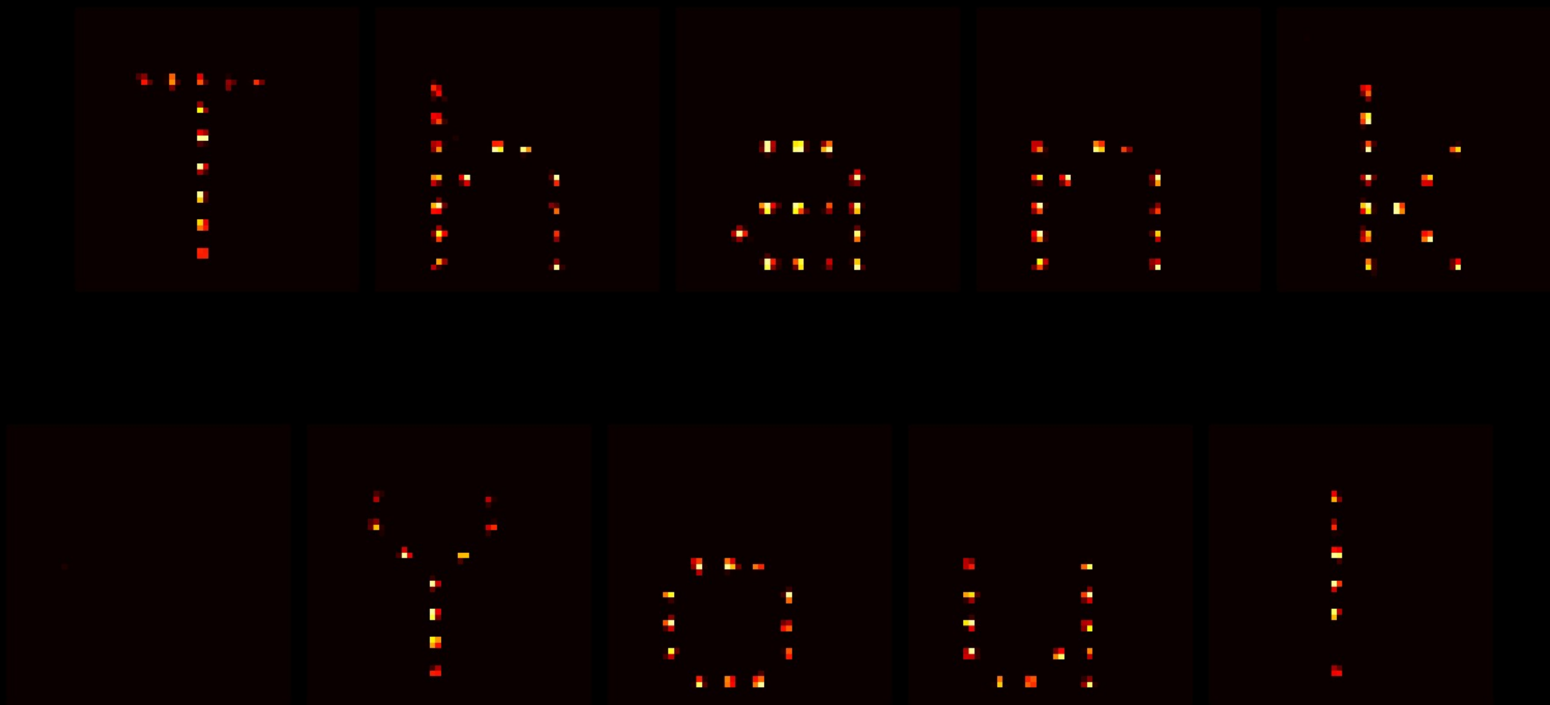
Thank You!