Quantum Simulation using Ultracold Atoms

Boulder Summer School 2023

MCQST

Munich Quantum Valley

QUANTUM FLAGSHIP

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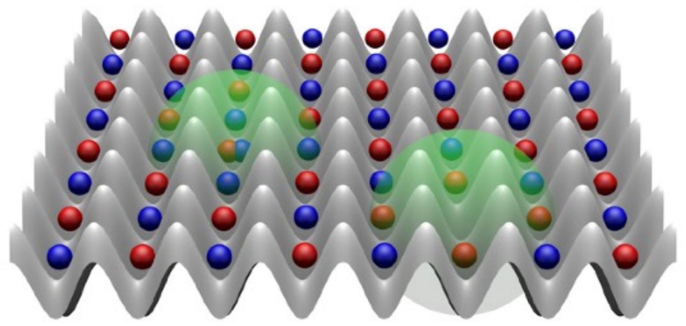
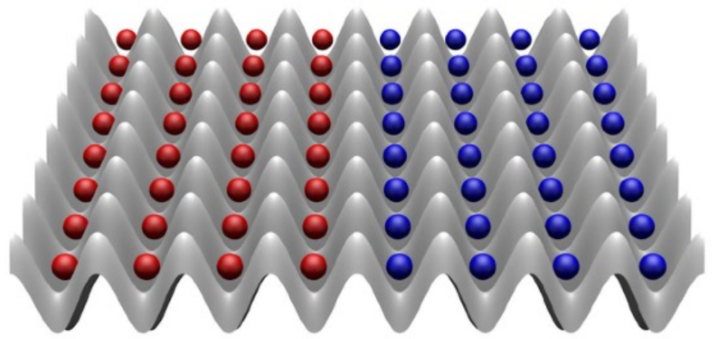
Bundesministerium für Bildung und Forschung

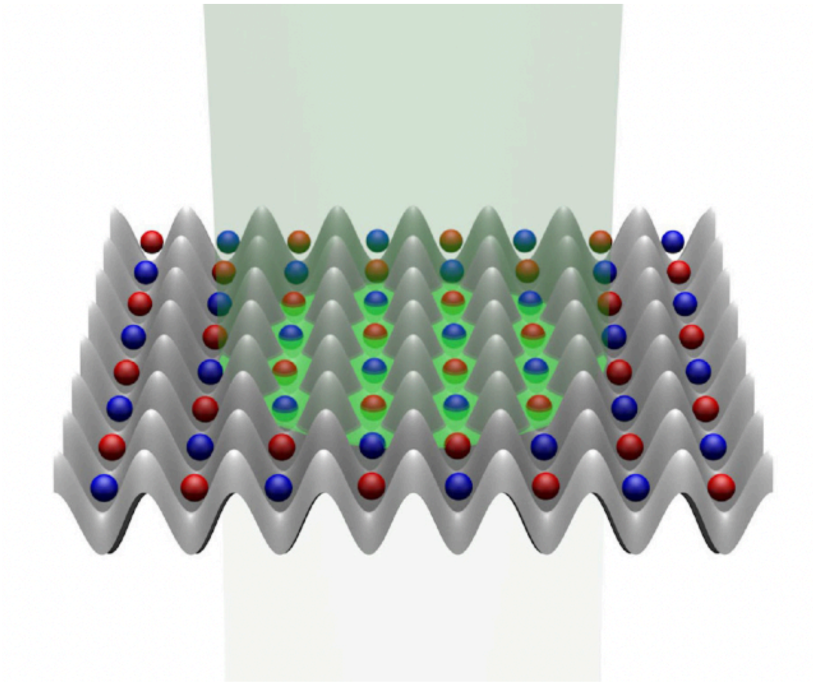
Lecture Outline



1 **Quantum Simulation & Computing using Ultracold Atoms**
Potentials, Interactions, Gates, Models….

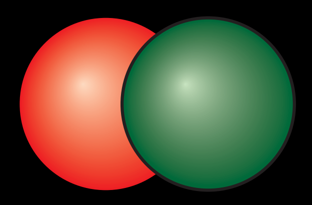


2 **Floquet Topological Quantum Matter & Quantum Gas Microscopy**
Topological Matter, Floquet Systems, Anomalous Floquet Topological Systems, Quantum Gas Microscopy, Dynamical Spin-Charge Fractionalisation

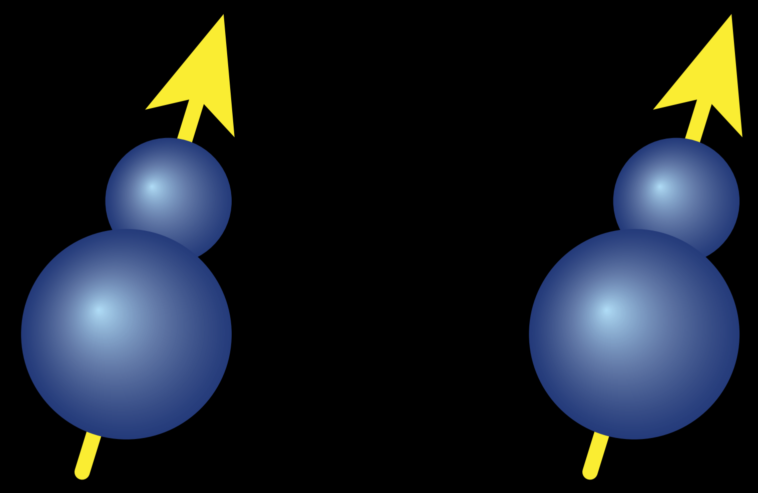


3 **Quantum Matter Out-Of-Equilibrium**
Many Body Localisation, Thermalization, Measuring Entanglement Entropy, Fluctuation Hydrodynamics, Anomalous Spin Transport (KPZ)

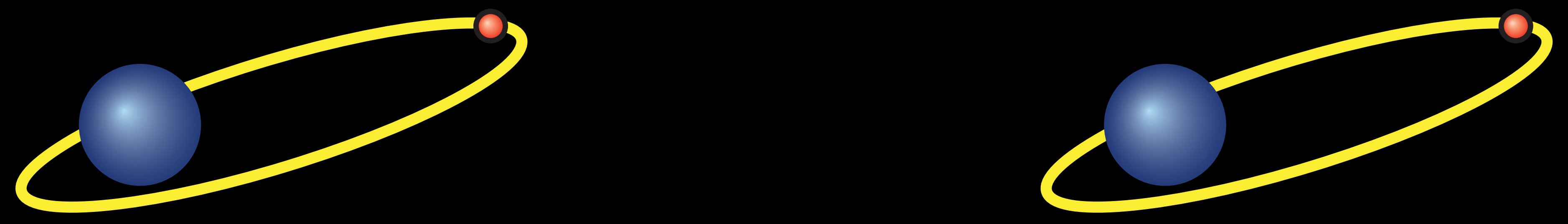
Interaction Control



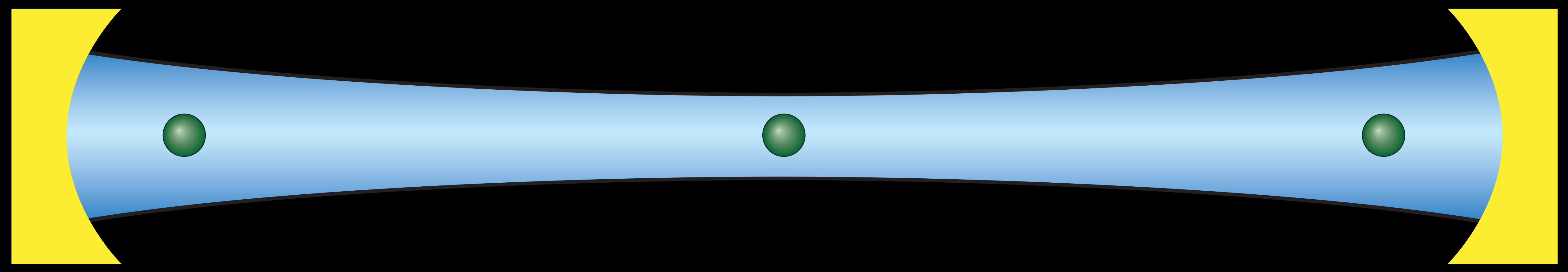
Collisional
(onsite few kHz)



Dipolar
Magnetic or Electric
(several sites Hz to 10 kHz)



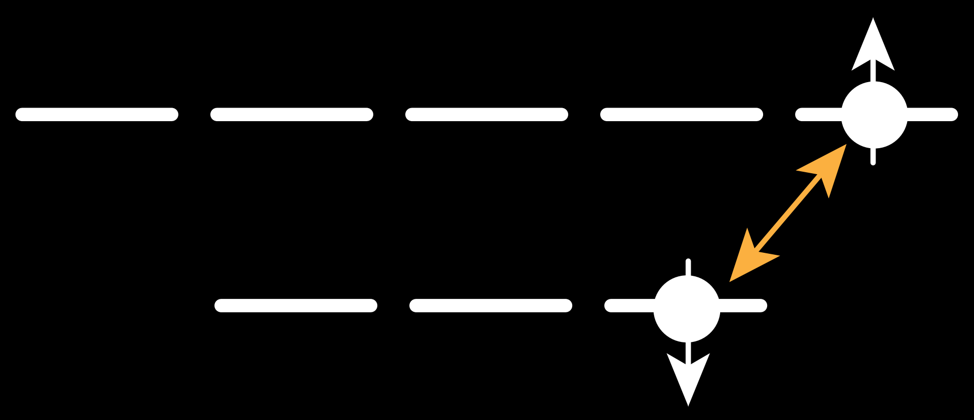
Rydberg Dipole-Dipole
(several sites 1-500 MHz)



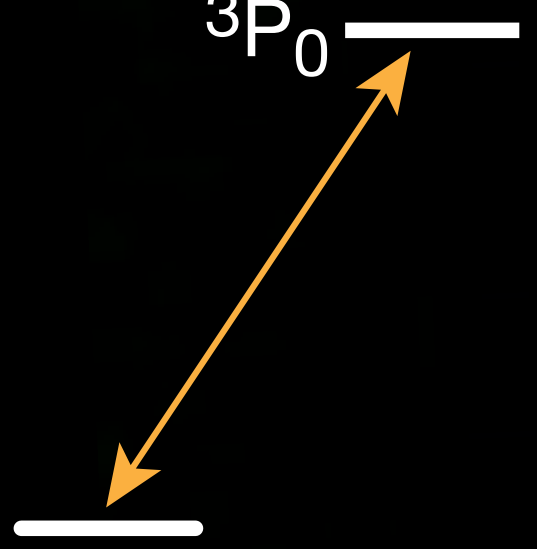
Cavity Mediated
(All-to-All few Hz-kHz)

Particles: Fermions, Bosons, Mixtures

Spin degree of freedom:



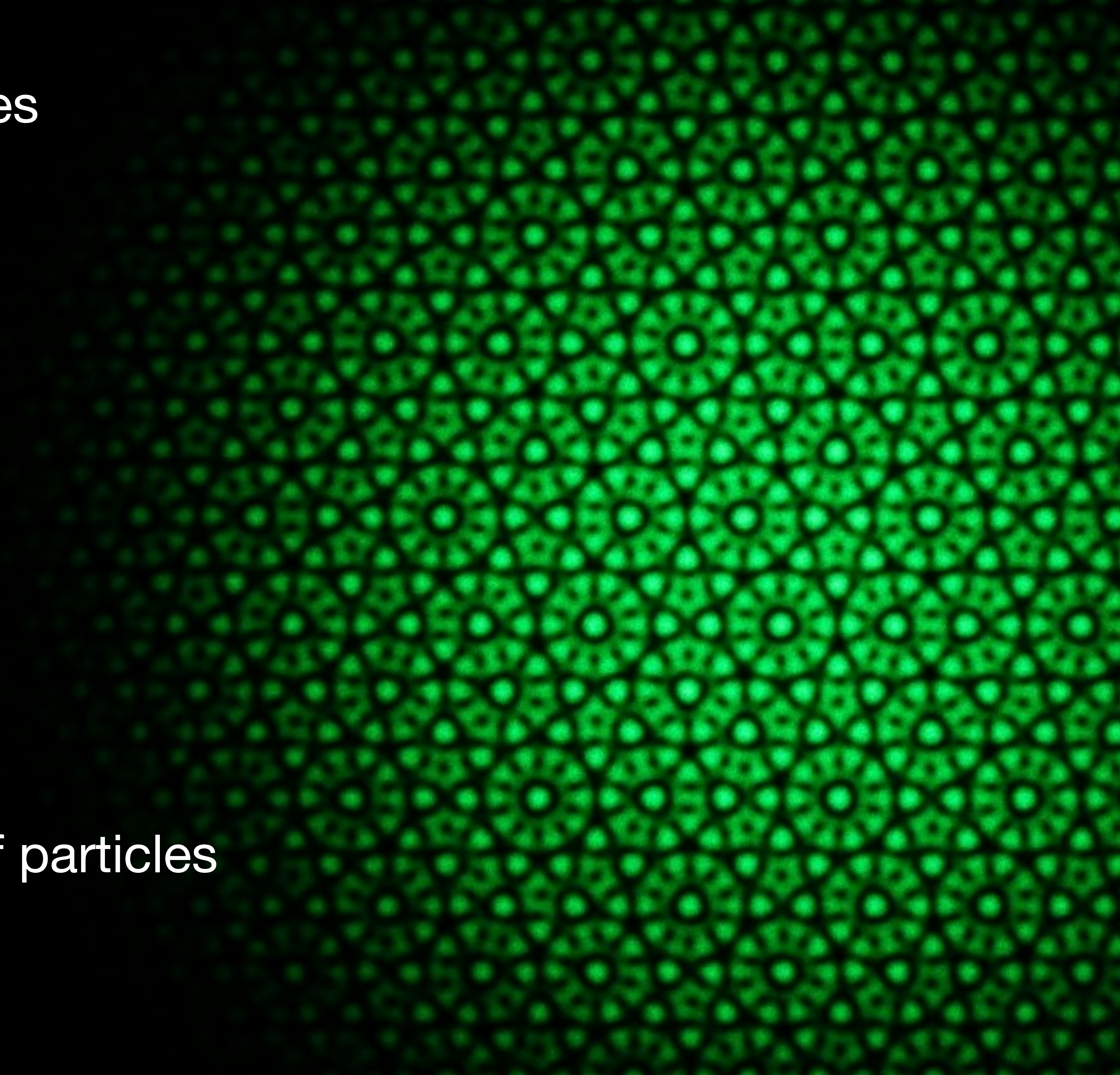
Hyperfine
(Microwave)



Clock
(Optical)

System size: up to few thousands of particles

Mobility: itinerant or static



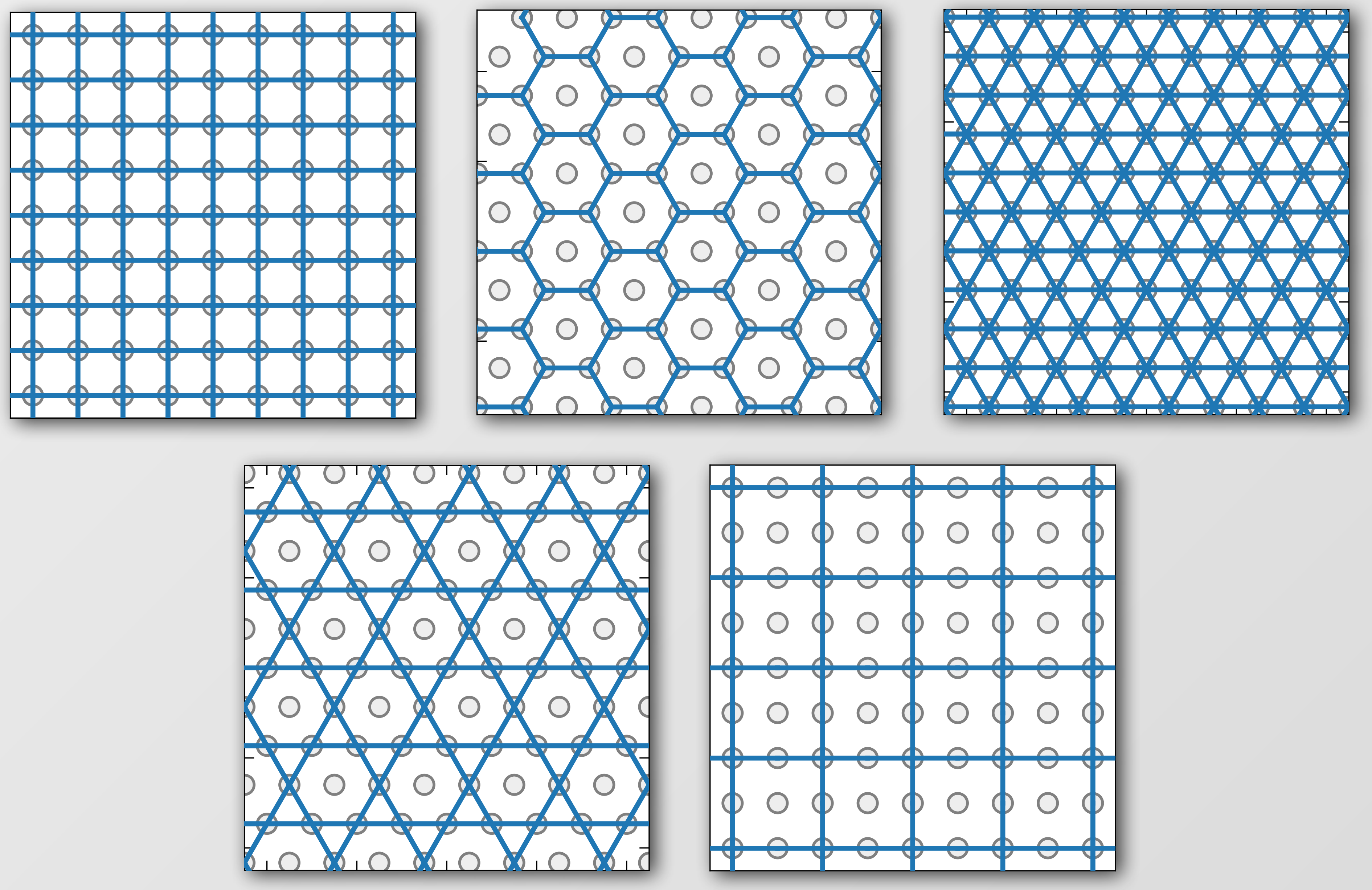
courtesy: T. W. Hänsch

Primer on Optical Lattices

Fourier synthesize aribtrary lattices:

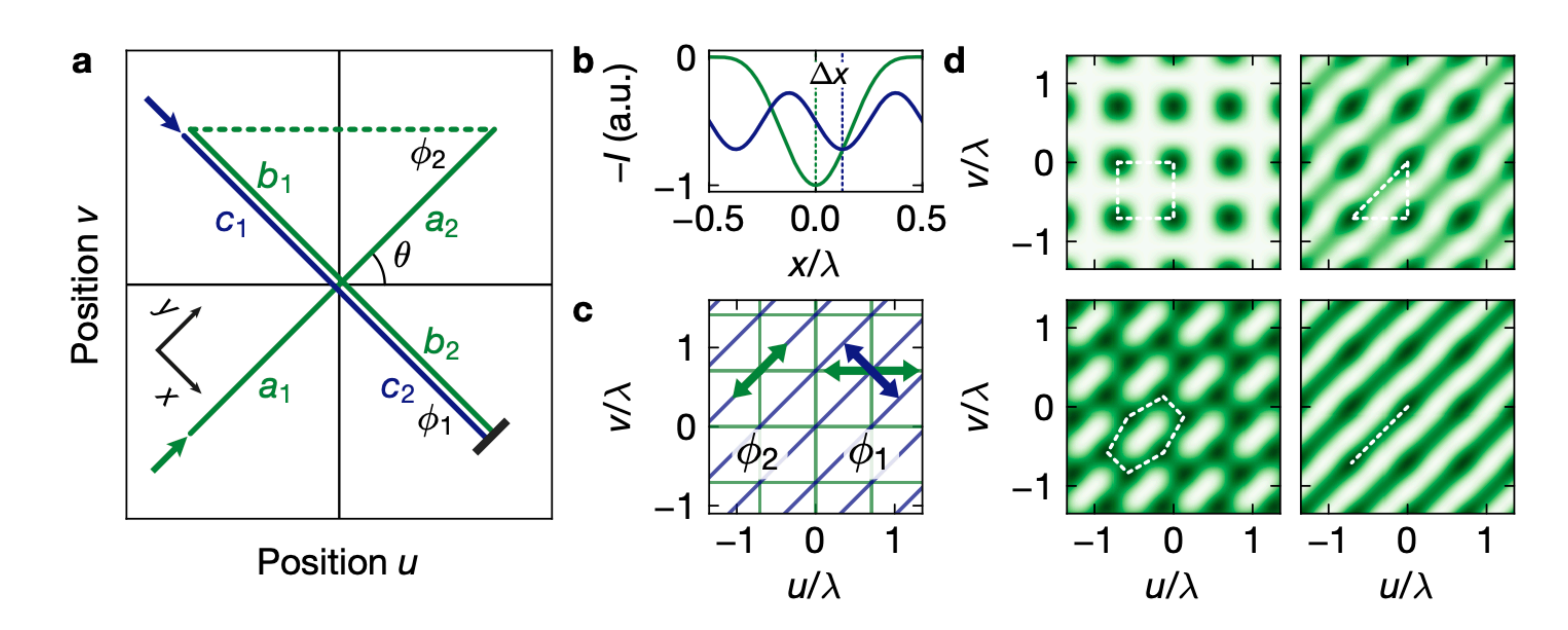
- Square
- Hexagonal/Triangular/Brick Wall
- Kagomé
- Superlattices
- *Spin dependent lattices*
- *Flux Lattices*

...



Full **dynamical** control over **lattice depth, geometry, dimensionality!**

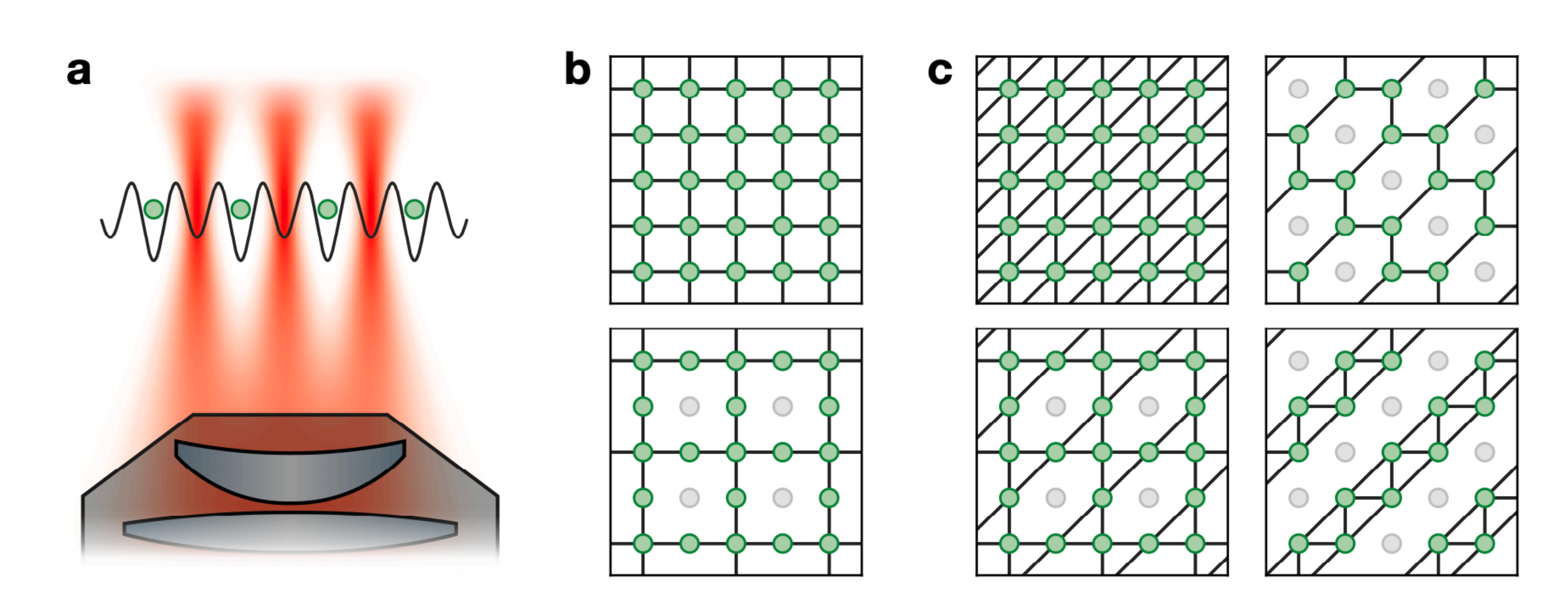
Flexible Lattice Geometry (I)



Phase stable setups yield

Square, Triangular, Hexagonal, Dimerised Lattices

Flexible Lattice Geometry (II)

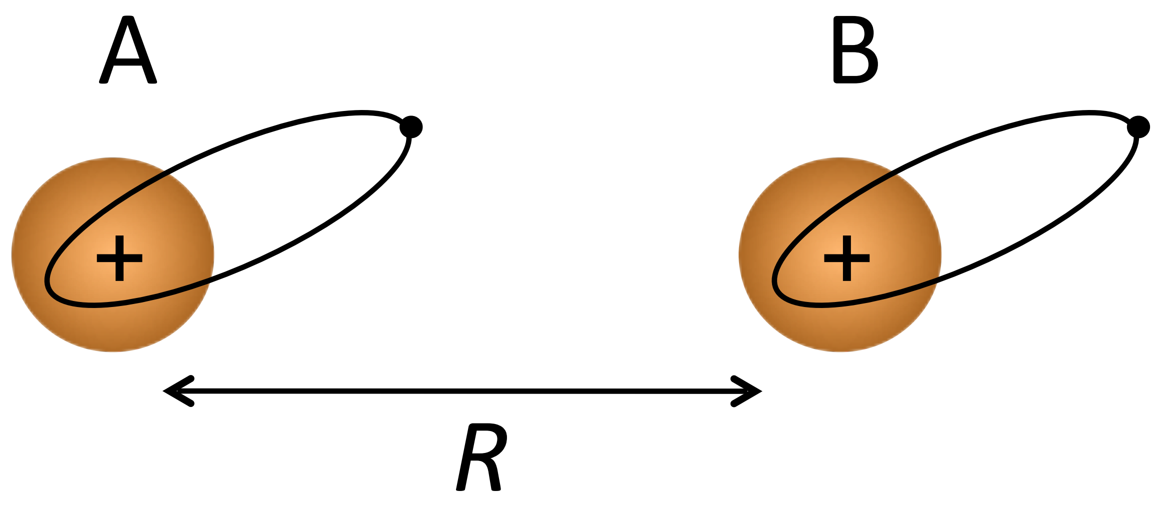


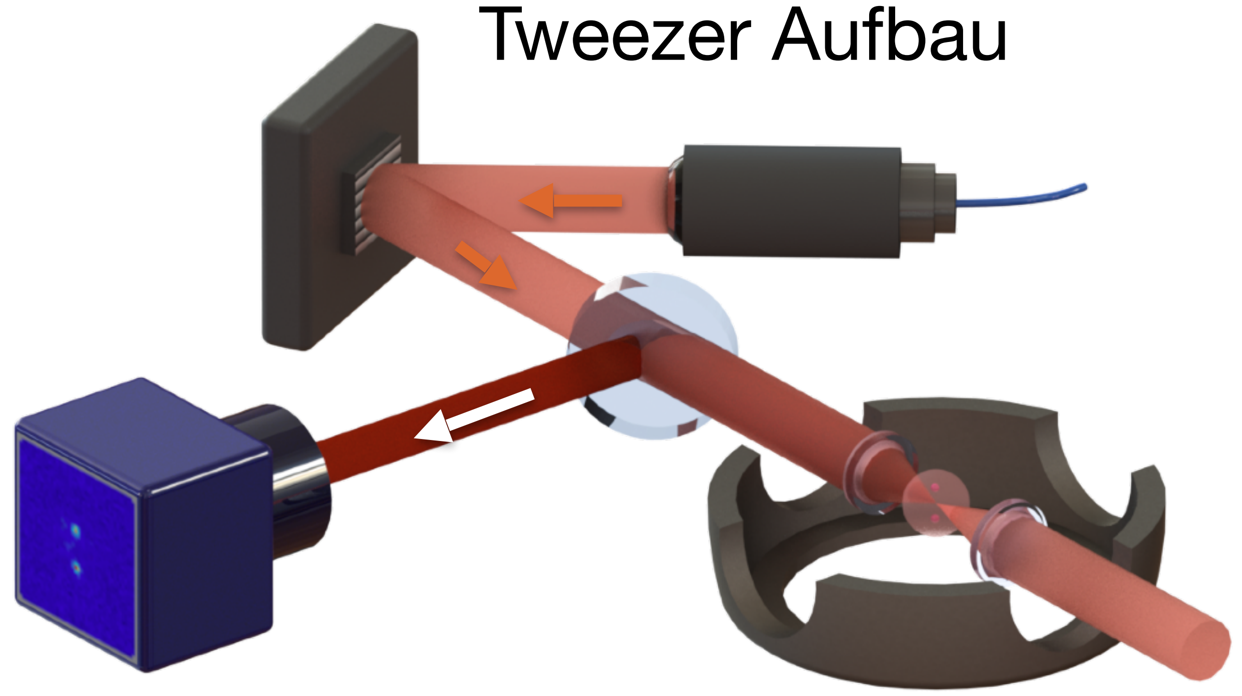
Blocking out sites gives additional flexibility:
Lieb lattice, Hexagonal, Kagome, Zig Zag,….

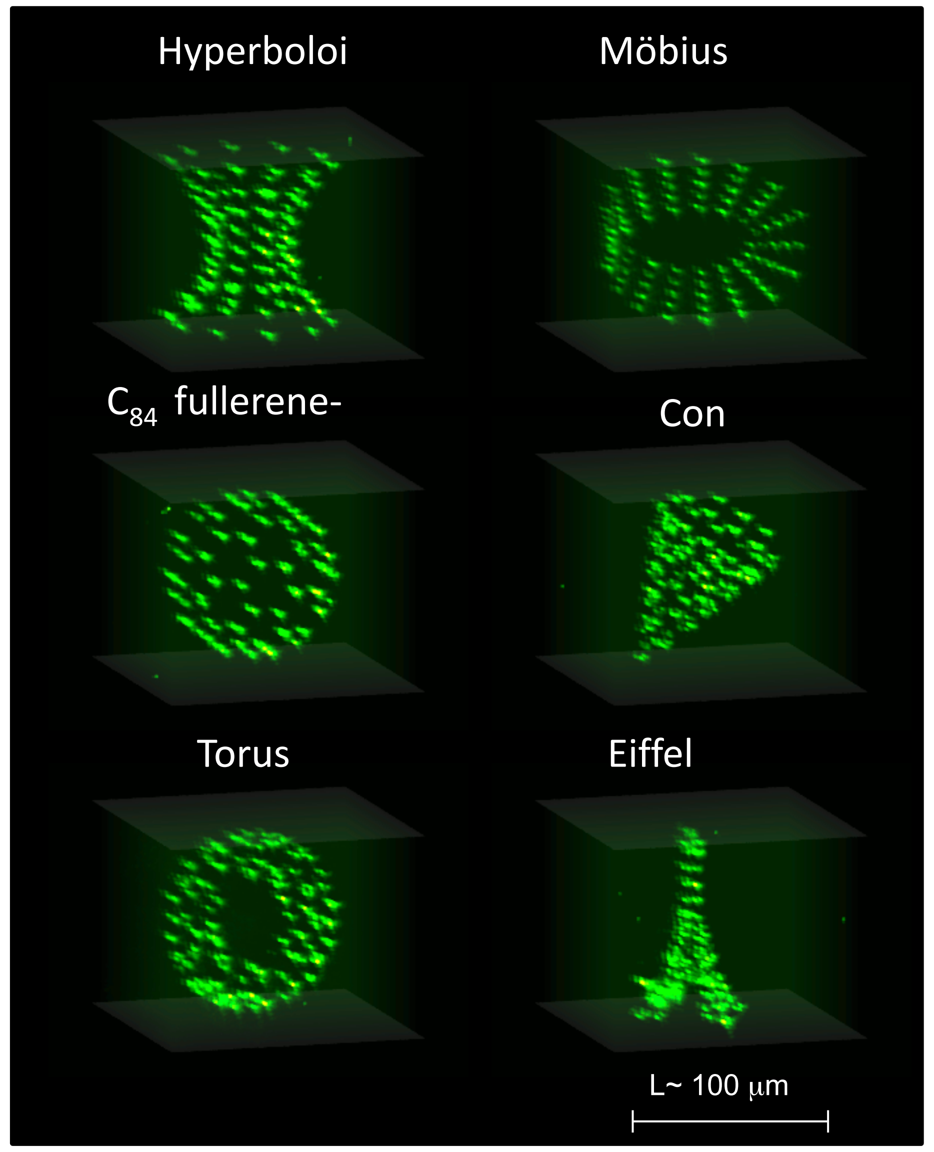
Single Atoms in Optical Tweezers

Neutral Atoms in Optical Tweezers

- Several 100 atoms, **individually addressable** via focused laser beams
- **Entanglement** via Rydberg-Rydberg Interactions (see discussion on interactions)

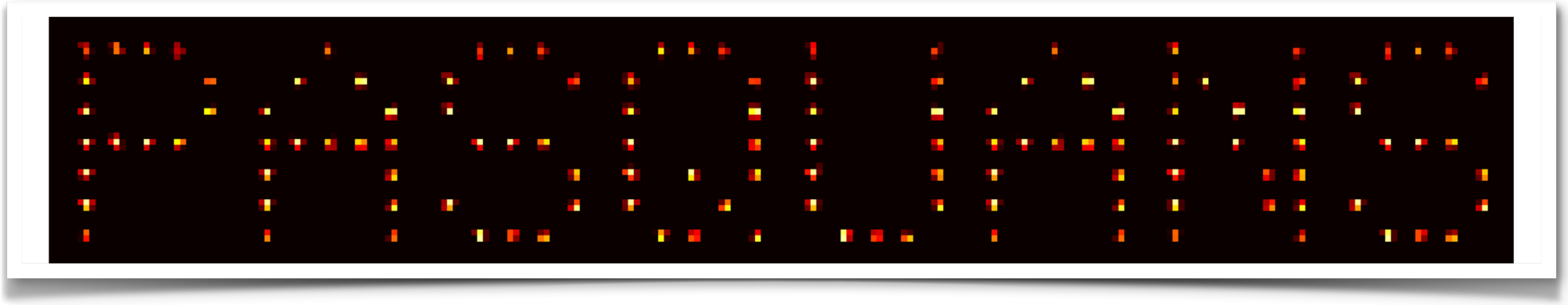






Barredo *et al.*, Nature (2018)

Flexible and dynamic trap geometries



See also: Lukin (Harvard), Endres (Caltech), Thompson (Princeton), Kaufman (JILA), Bernien (Chicago), Zeiher (MPQ)….

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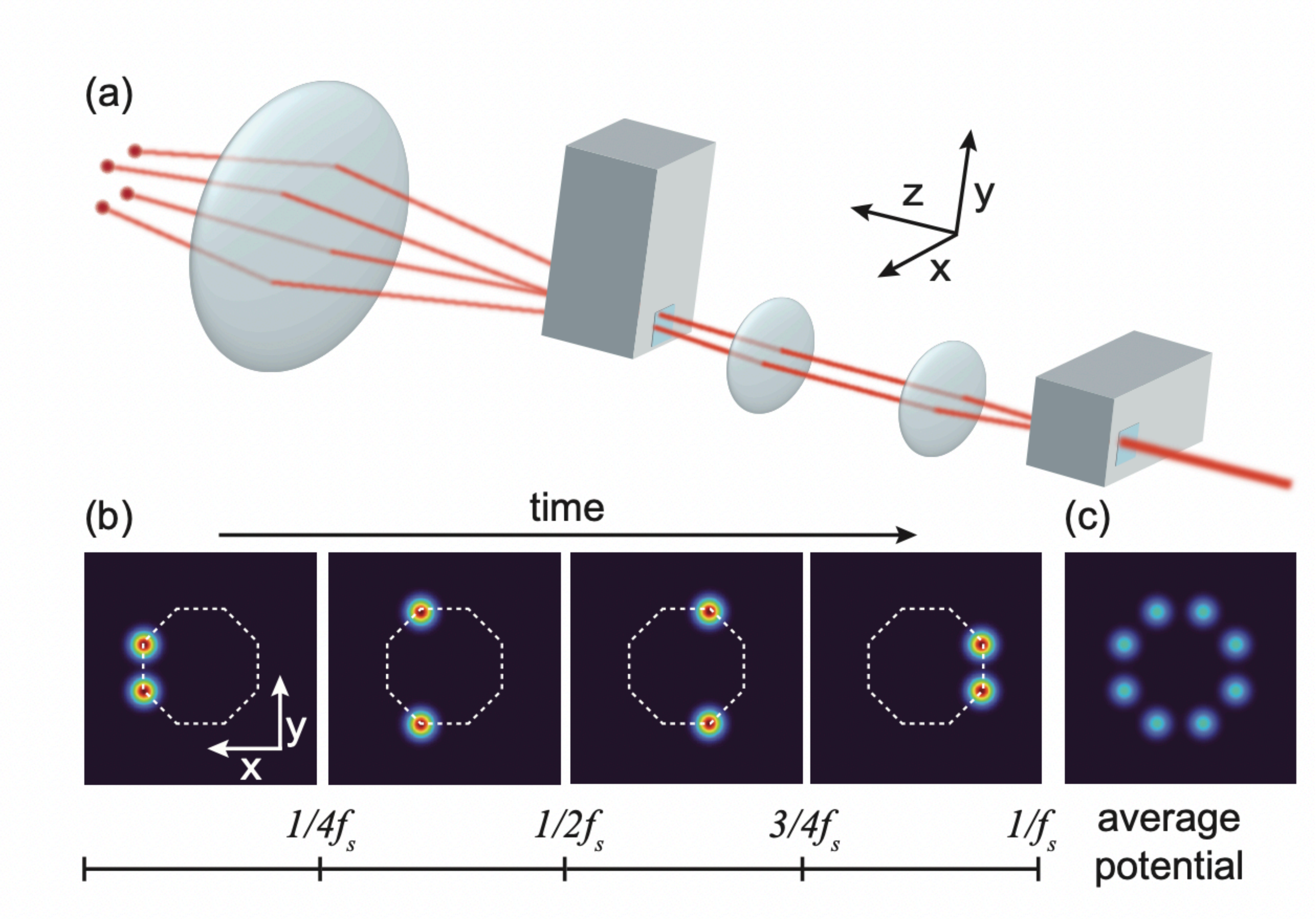
Collège de France
cnrs

Hubbard Regime Tweezer Arrays

Zoe Z. Yan,…,W. Bakr, Phys. Rev. Lett. **129,** 123201 (2022)



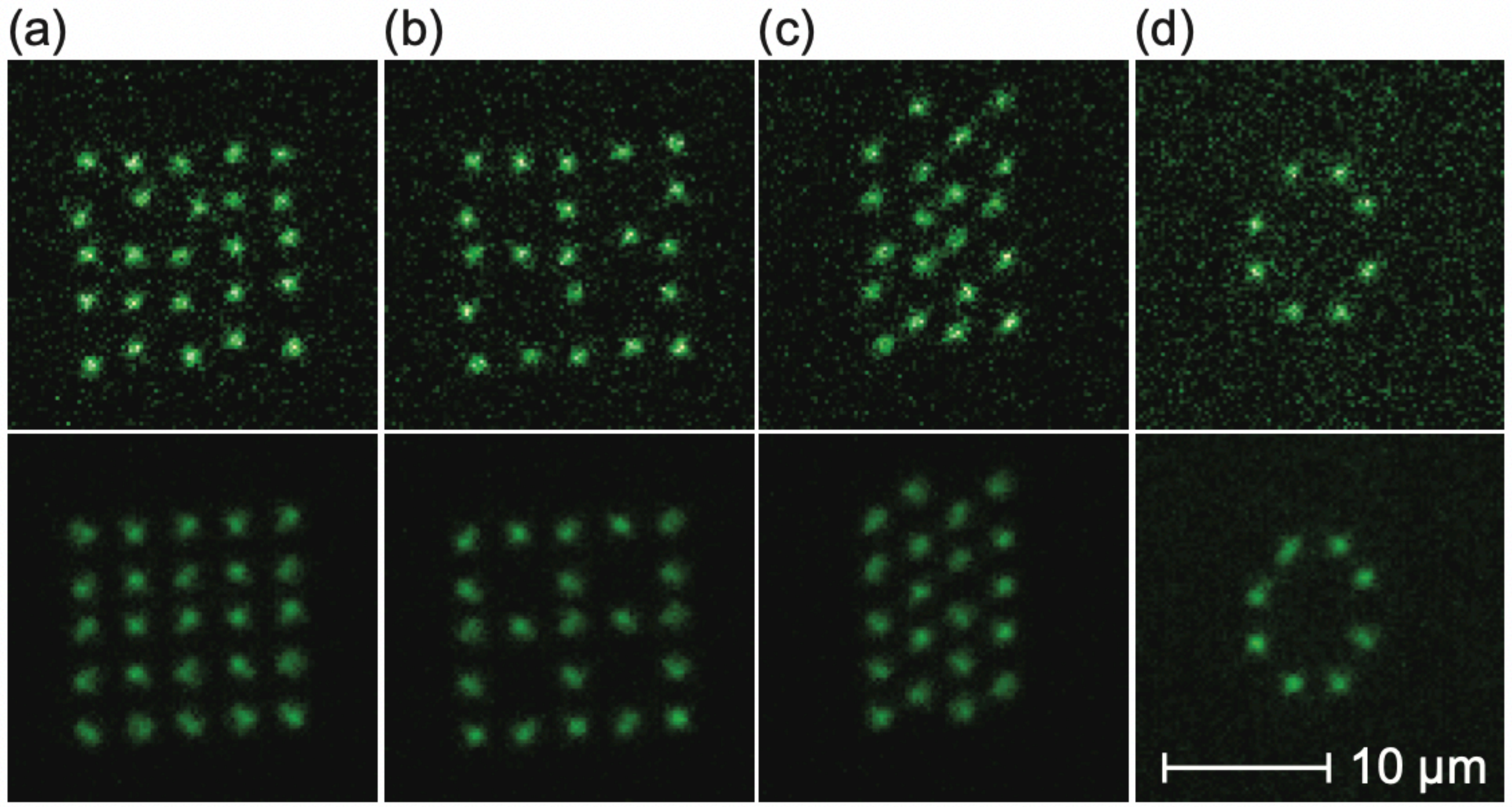
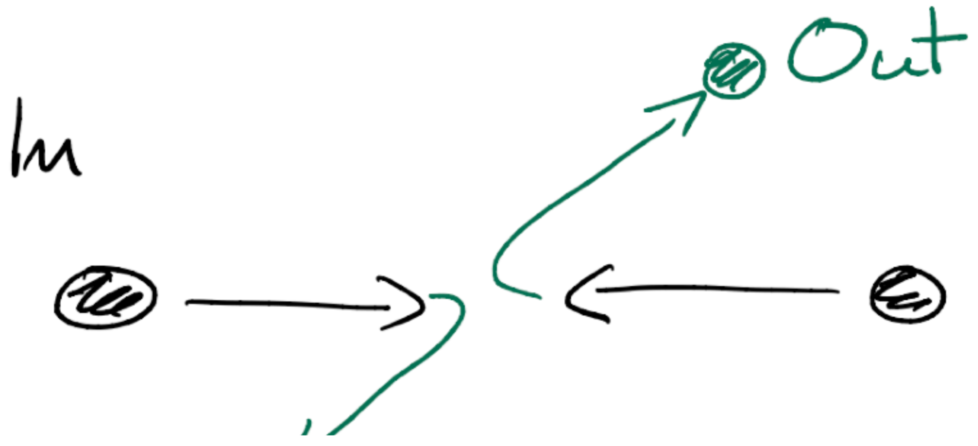


FIG. 2. Examples of band insulators of different geometries,
showing … uette, (3)
4 × 5 trian… |↑⟩atoms
are image… . The top
row show… state, and
the botto… the atom
positions… antization
onto the … are (93,
92, 91, 8… %, out of
(411, 254 … shots.

- Flexible Geomtry
- Dynamical
- Homogeneity
- Larger Spacing

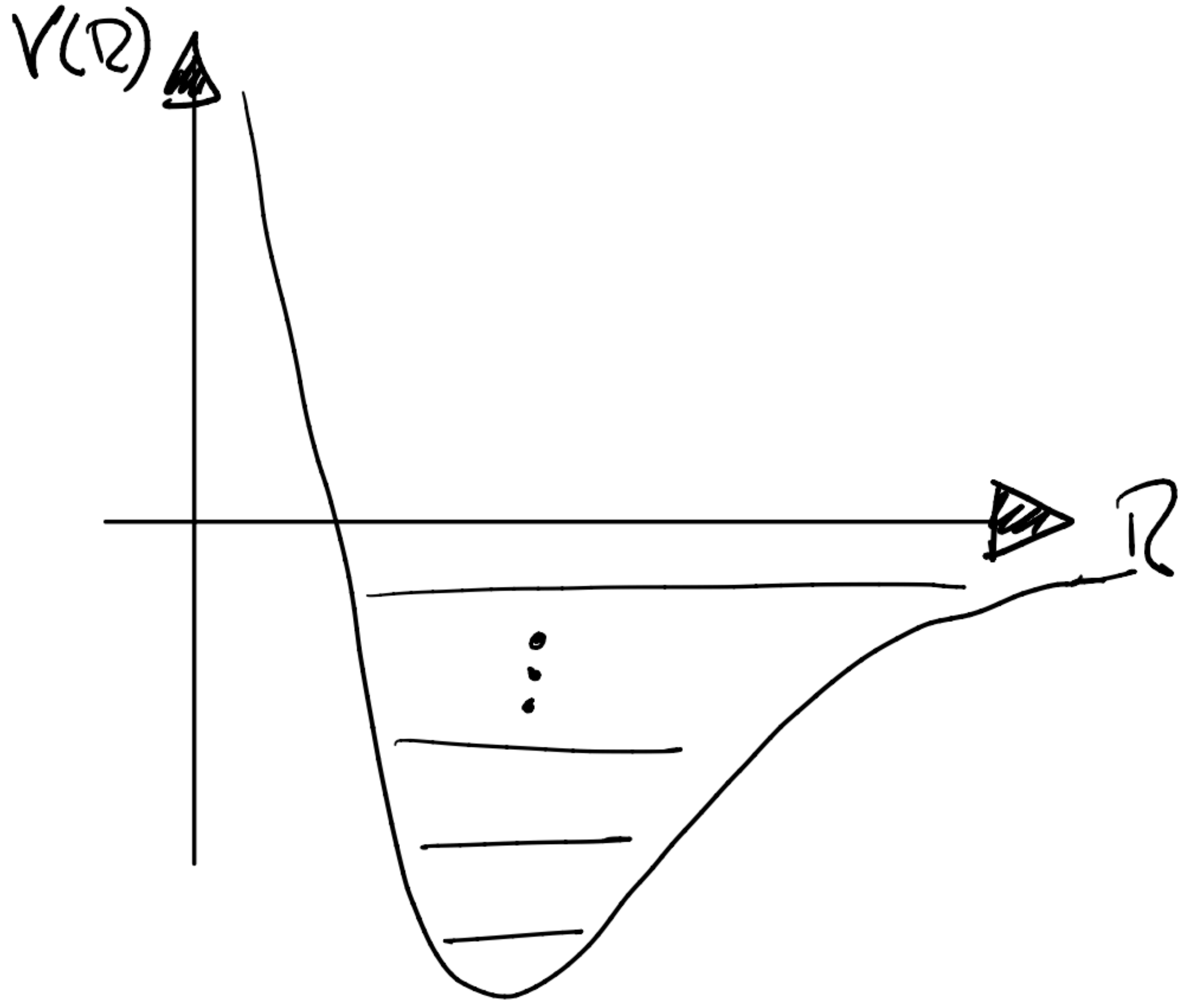
Collisional Interactions



Bosons: Symmetric WF

Fermions: Anti-symmetric WF

Interaction Potential



$\Longleftrightarrow$

$$\frac{4\pi\hbar^2 a}{m}\,\delta(\vec{r})$$

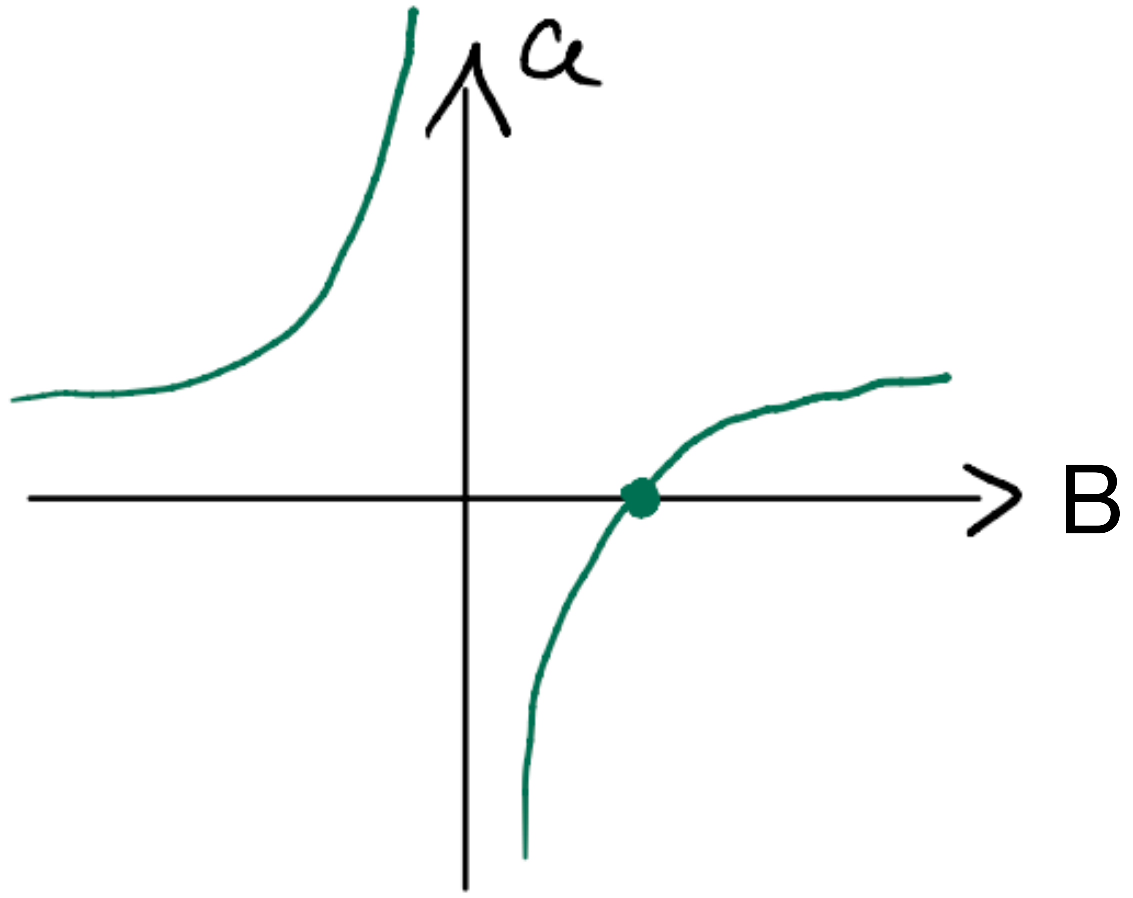
$a \mathrel{\hat{=}}$ scattering length

Born-Oppenheimer Potential

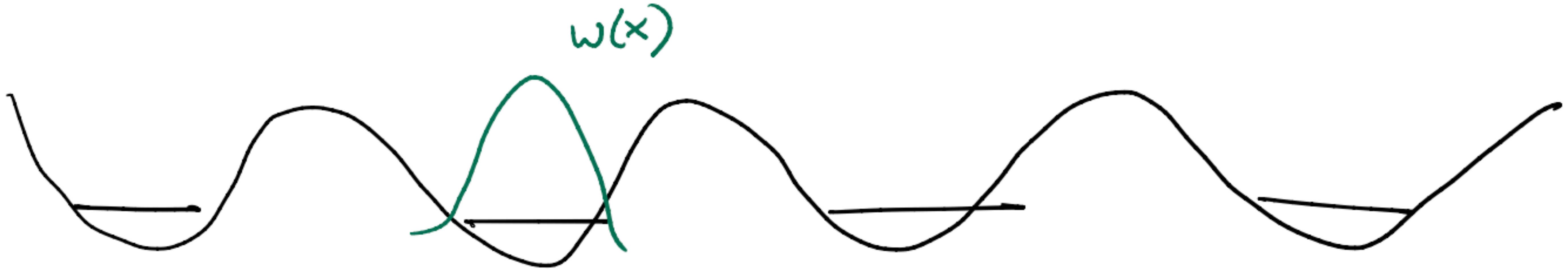
Pseudopotential

Feshbach Resonances

$$a(B) = a_{bg}\left(1 + \frac{\Delta}{B - B_0}\right)$$



Lattice (or tightly focused tweezer)



$$U = \frac{4\pi\hbar^2 a(B)}{m} \int |w(\vec{r})|^4 \, d^3r$$

$$H = -J\sum_{\langle i,j\rangle} \hat{a}_i^\dagger \hat{a}_j + \sum_i \varepsilon_i \hat{n}_i + \frac{1}{2}U\sum_i \hat{n}_i(\hat{n}_i - 1)$$

Bose-Hubbard

$$\hat{H} = -J\sum_{\langle i,j\rangle,\sigma} \hat{c}_{i,\sigma}^\dagger \hat{c}_{j,\sigma} + U\sum_i \hat{n}_{i,\downarrow}\hat{n}_{i,\uparrow} + V_t\sum_{i,\sigma} i^2 \hat{n}_{i,\sigma}$$

Fermi-Hubbard

to the Heisenberg spin-1/2 model (half filling, strong interactions)

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

$$J = \frac{4t^2}{U}$$

(Or more generally XXZ Hamiltonian)

Collisional Quantum Gates

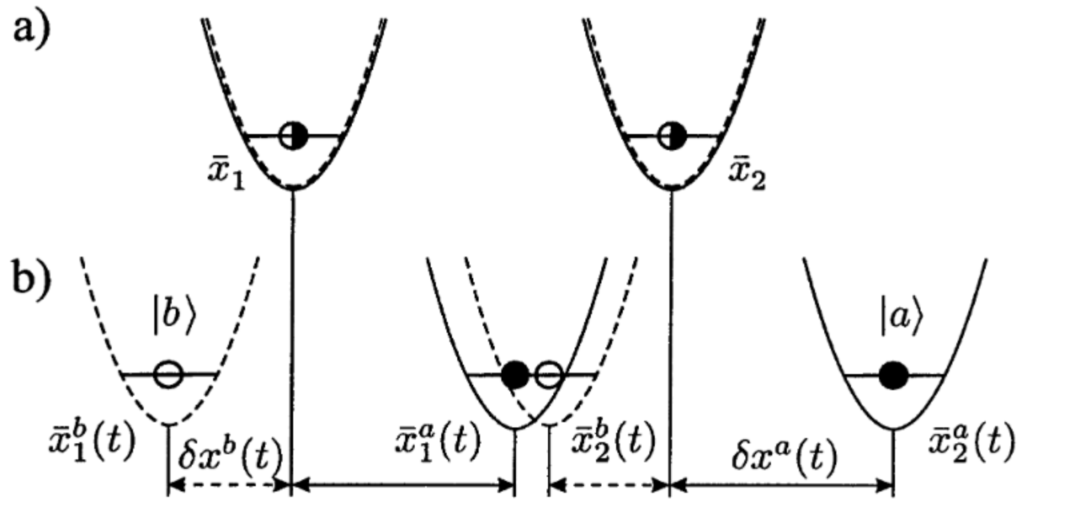
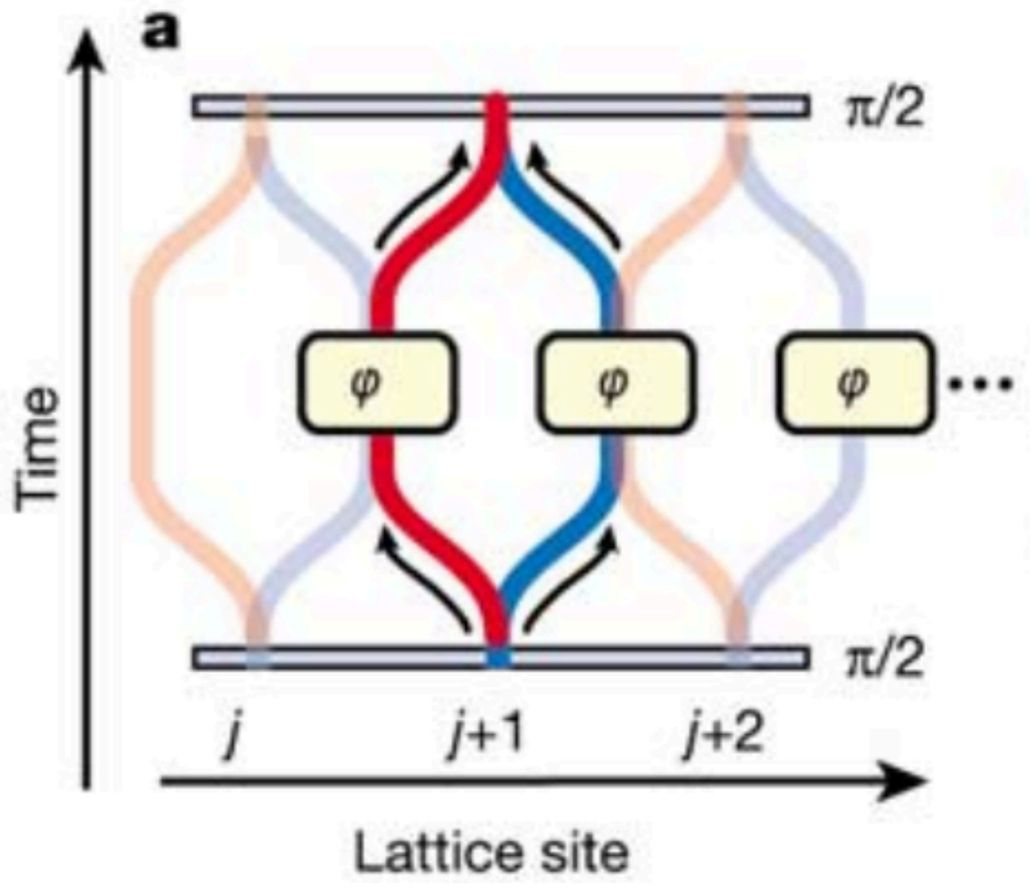


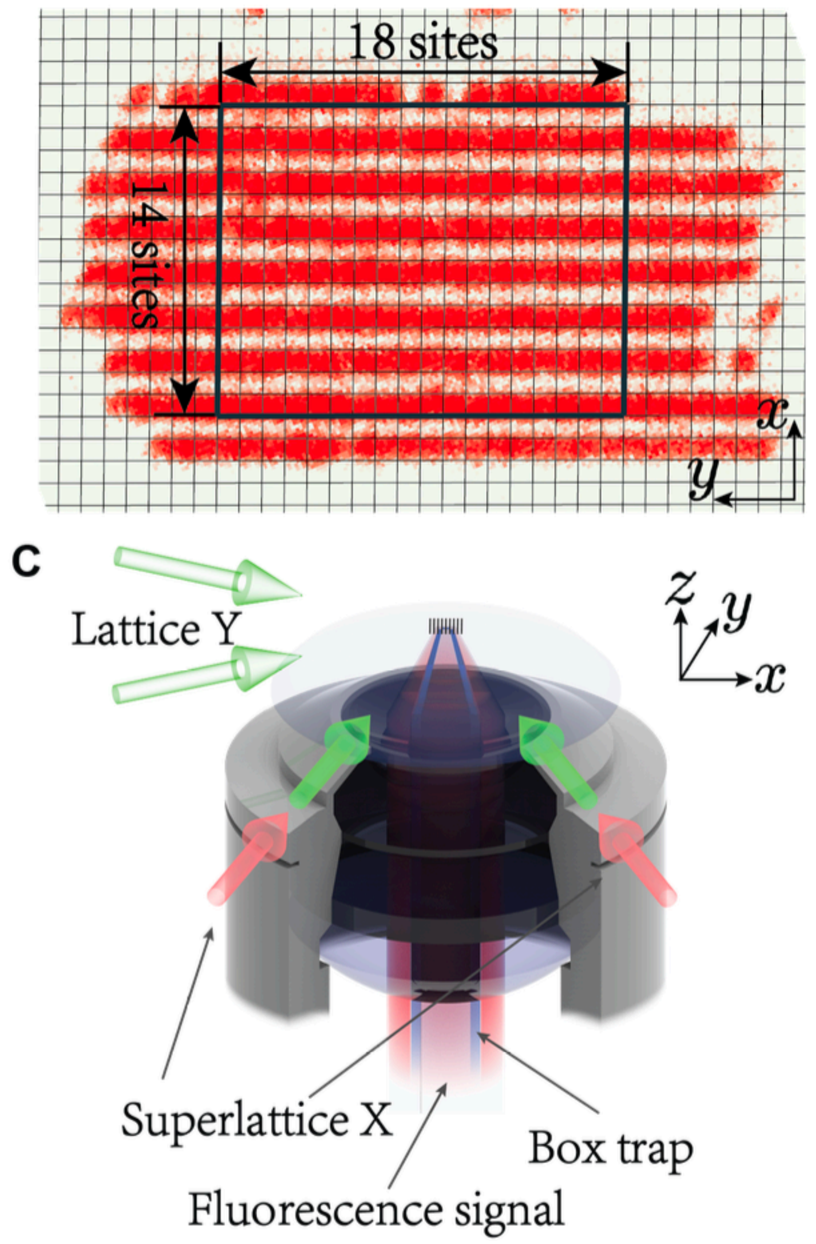
FIG. 1. Configurations at times $\pm\tau$ (a) and at t (b). The solid (dashed) curves show the potentials for particles in the internal state $|a\rangle$ ($|b\rangle$), respectively. Center positions $\bar{x}_j^\beta(t)$ and displacements $\delta x^\beta(t)$ are as defined in the text.

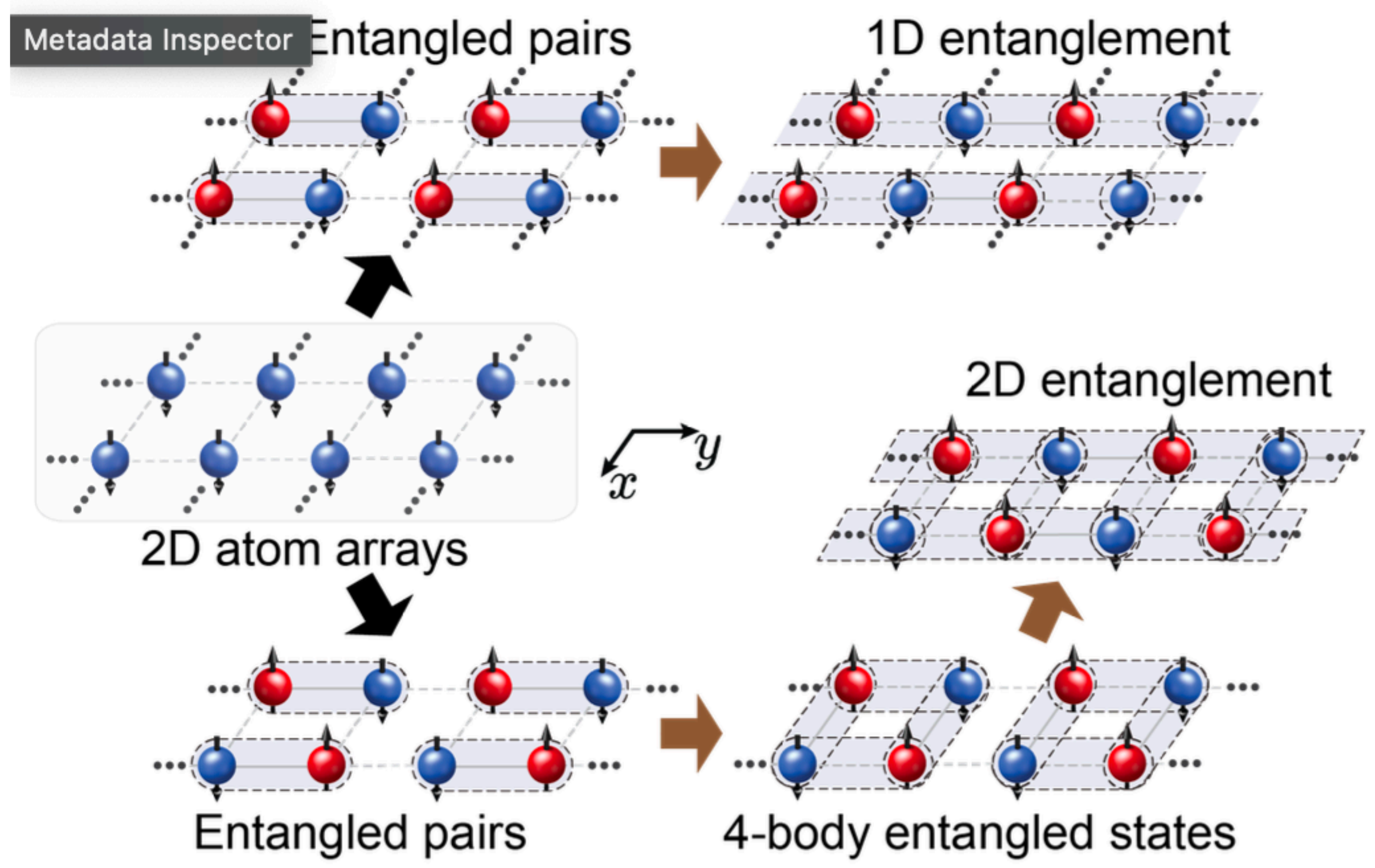


D. Jaksch, et al. Phys. Rev. Lett. **82**, 1975 (1999)
O. Mandel, et al. Nature **425**, 937 (2003)

Functional building blocks for scalable multipartite entanglement in optical lattices

Wei-Yong Zhang,[1,2,*] Ming-Gen He,[1,2,*] Hui Sun,[1,2,*] Yong-Guang Zheng,[1,2] Ying Liu,[1,2] An Luo,[1,2] Han-Yi Wang,[1,2] Zi-Hang Zhu,[1,2] Pei-Yue Qiu,[1,2] Ying-Chao Shen,[1,2] Xuan-Kai Wang,[1,2] Wan Lin,[1,2] Song-Tao Yu,[1,2] Bin-Chen Li,[1,2] Bo Xiao,[1,2] Meng-Da Li,[1,2] Yu-Meng Yang,[1,2] Xiao Jiang,[1,2] Han-Ning Dai,[1,2] You Zhou,[1,3] Xiongfeng Ma,[4] Zhen-Sheng Yuan,[1,2,5] and Jian-Wei Pan[1,2,5]

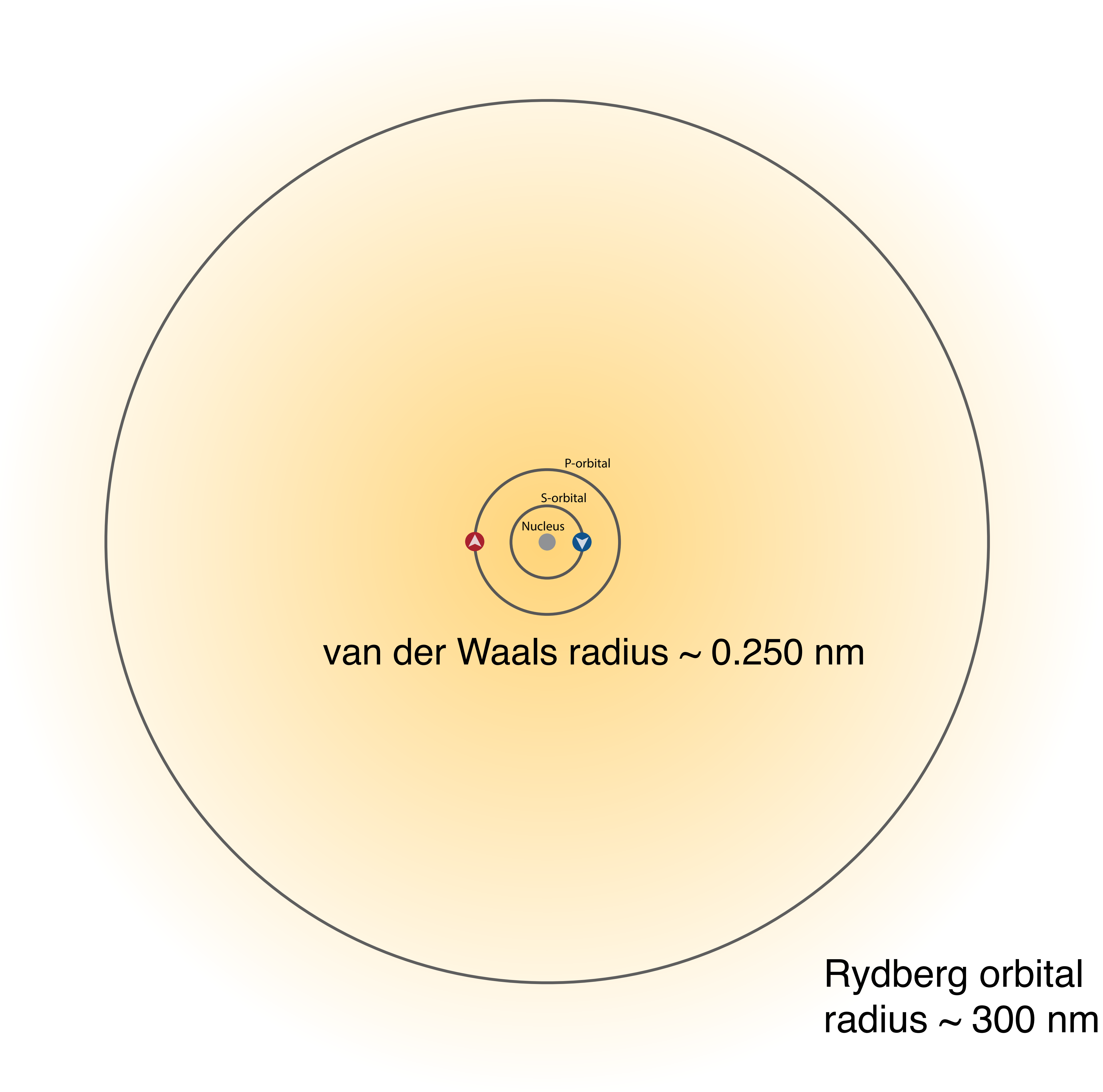




Two-Qubit Gate Fidelity
SQRT(SWAP) = 99.3%

B. Yang, B. et al. Science **369**, 550 (2020)
Zhang, W.-Y. et al. arXiv:2210.02936

Giant Rydberg Atoms



Rydberg orbital
radius ~ 300 nm for n ~ 60

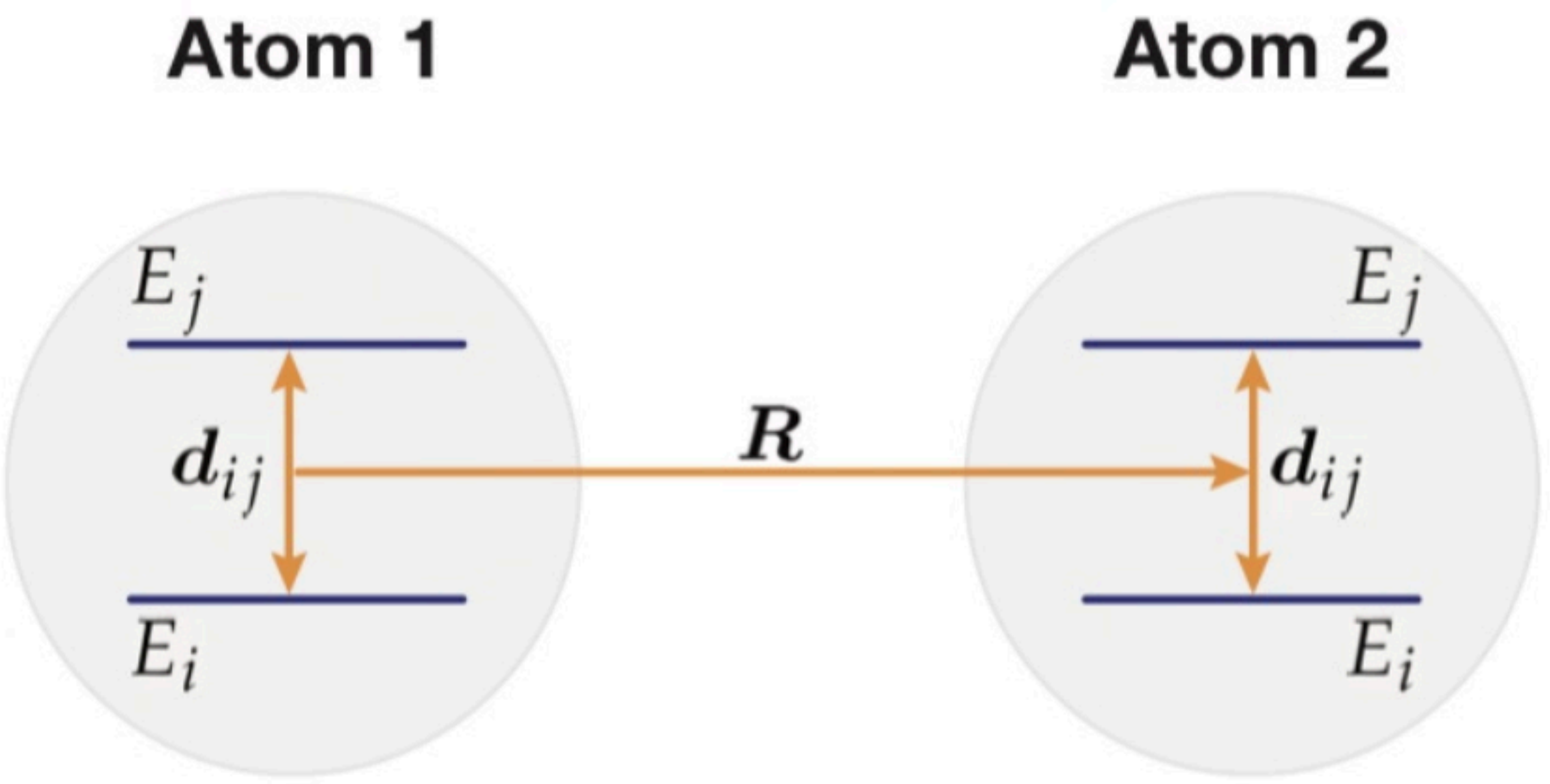
Quantity	Symbol	Scaling	Ref.	Values for $31P_{3/2}$
Energy	$E_{n,L,J}$	n^{-2}	[90, 91]	-4.1 THz
Orbital radius	$\langle r^2 \rangle^{1/2}$	n^2	[91]	67 nm
Coupling to $5S_{1/2}$	$\mathcal{R}^{n',1,J'}_{5,0,1/2}$	$n^{-3/2}$	[92]	$0.0036\, ea_0$
Coupling to $nS_{1/2}$	$\mathcal{R}^{n,1,J'}_{n,0,1/2}$	n^2	[92]	$899\, ea_0$ (to $31S_{1/2}$)
Effective lifetime	τ	n^2	[93]	28 µs
Radiative lifetime	τ_{rad}	n^3	[91, 93]	58 µs
Black-body lifetime	τ_{BB}	n^2	[91, 93, 94]	53 µs
Energy splitting	$\Delta E_{n,L,J}$	n^{-3}	[90, 91]	-145 GHz (to $31S_{1/2}$)
C_6-coefficient	C_6	n^{11}	[92, 95]	$-h\, 201$ MHz µm^6
Blockade radius	R_b, R_c	$\sim n^{1.8}$		1.43 µm ($\Delta/2\pi = 6$ MHz)

drawing not to scale!

Interactions in two-state model

For simplicity, we assume

$$V(R) = \frac{|\vec{d}|^2}{4\pi\varepsilon_0 R^3} \qquad (\text{dipoles} \perp \vec{e}_R)$$



$$H = \begin{array}{c} \\ |i,i\rangle \\ |i,j\rangle \\ |j,i\rangle \\ |j,j\rangle \end{array} \begin{array}{c} \begin{array}{cccc} \langle i,i| & \langle i,j| & \langle j,i| & \langle j,j| \end{array} \\ \begin{pmatrix} 0 & 0 & 0 & V \\ 0 & \hbar\Delta & V & 0 \\ 0 & V^\star & \hbar\Delta & 0 \\ V^\star & 0 & 0 & 2\hbar\Delta \end{pmatrix} \end{array}$$

Rydberg - Direct Exchange Interactions

Start with atoms in <u>different</u> initial states $|i,j\rangle \leftrightarrow |j,i\rangle$

Atoms initially in <u>different states</u>!

$$|\pm\rangle = \frac{1}{\sqrt{2}}\left(|i,j\rangle \pm |j,i\rangle\right)$$

$$E_\pm = \Delta \pm |V|$$

<u>Resonant exchange</u>

⇝ Resonant exchange oscillations

$$\omega_{ex} = 2|V|/\hbar$$

Rydberg - van der Waals

Atoms initially in same state !

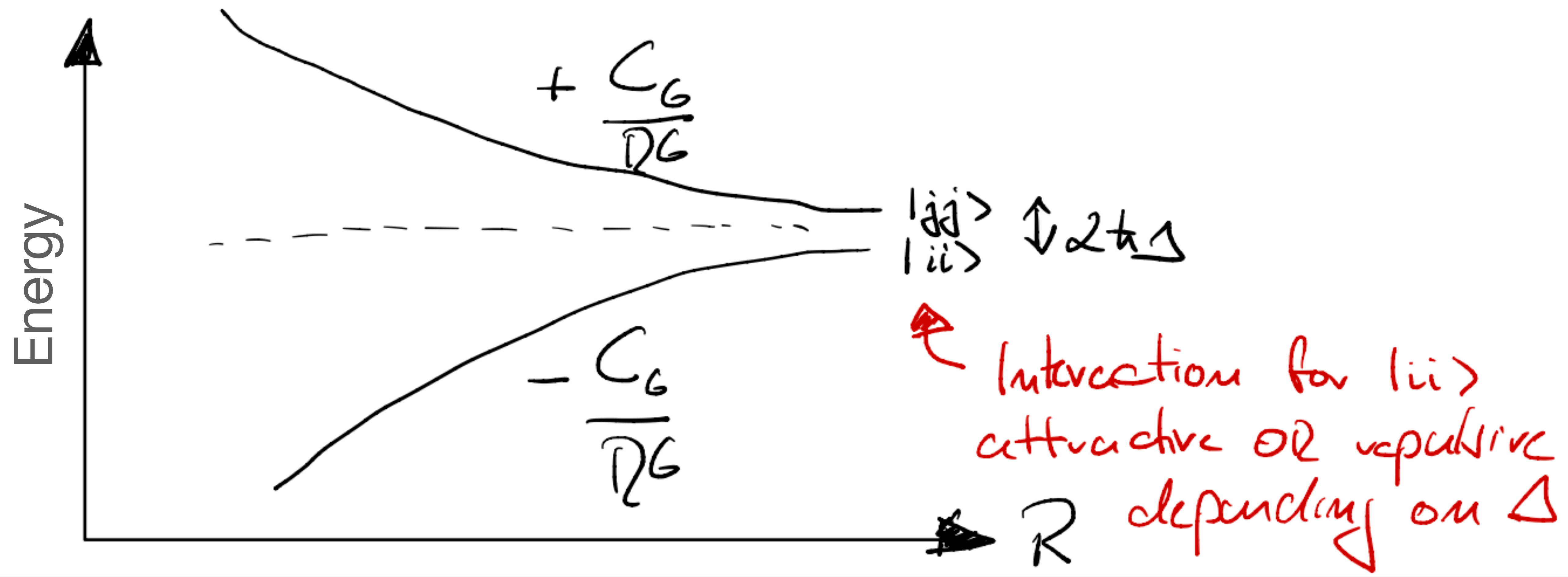
$$H_{\mathrm{vdW}} = \begin{array}{c} \\ |i,i\rangle \\ |j,j\rangle \end{array} \begin{array}{cc} \langle i,i| & \langle j,j| \\ \left(\begin{array}{c} 0 \\ V^{\star} \end{array}\right. & \left.\begin{array}{c} V \\ 2\hbar\Delta \end{array}\right) \end{array}.$$

detuned coupling

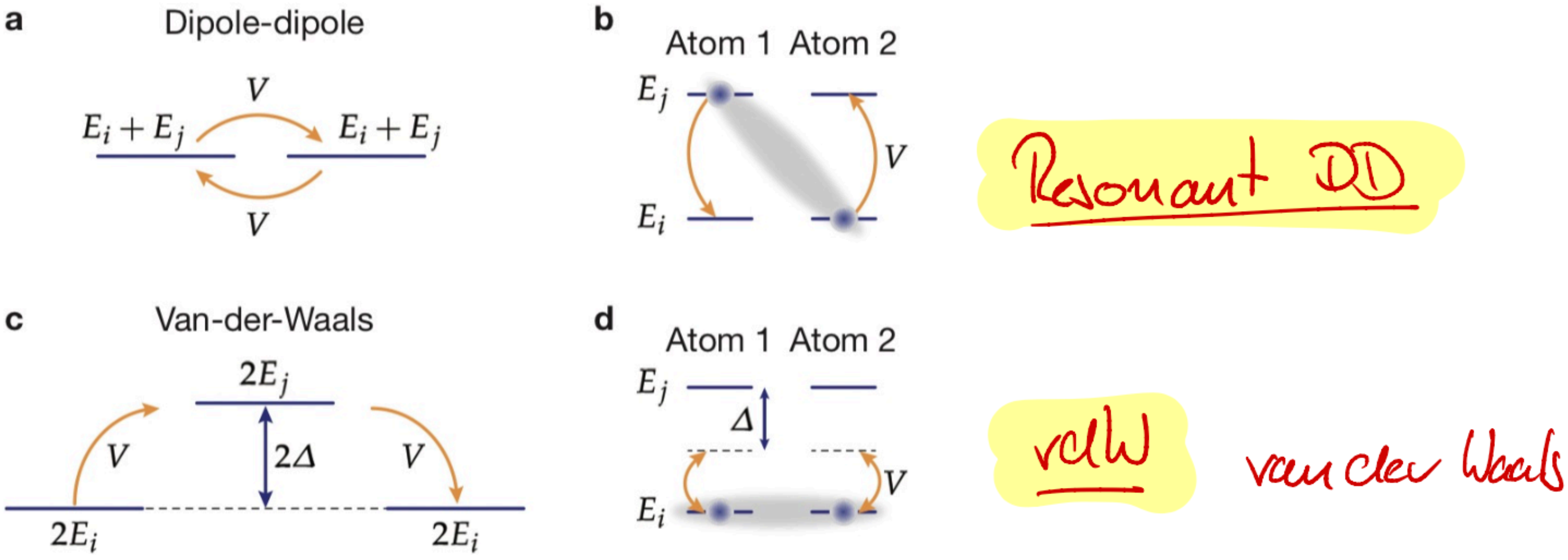
$$E_{-} = \hbar\Delta - \sqrt{(\hbar\Delta)^2 + |V|^2}$$

$$\approx \hbar\Delta - \hbar|\Delta| - \frac{|V|^2}{2\hbar|\Delta|} = -\frac{|\boldsymbol{d}|^4}{32\pi^2\epsilon_0^2\hbar|\Delta|R^6} \equiv -\frac{C_6}{R^6},$$

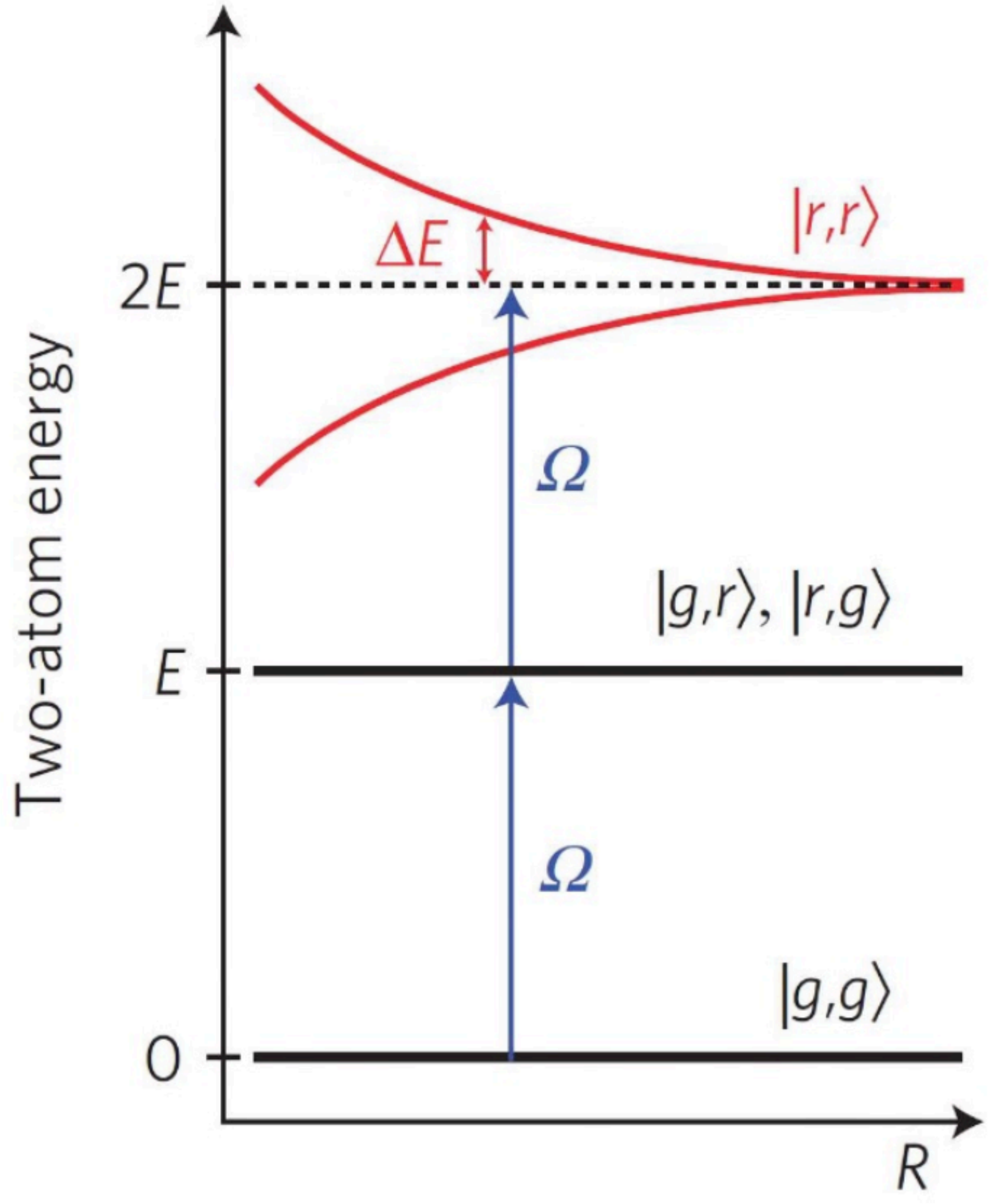
$$E_+ = +\frac{C_6}{R^6}$$



Rydberg - Summary



Rydberg Blockade

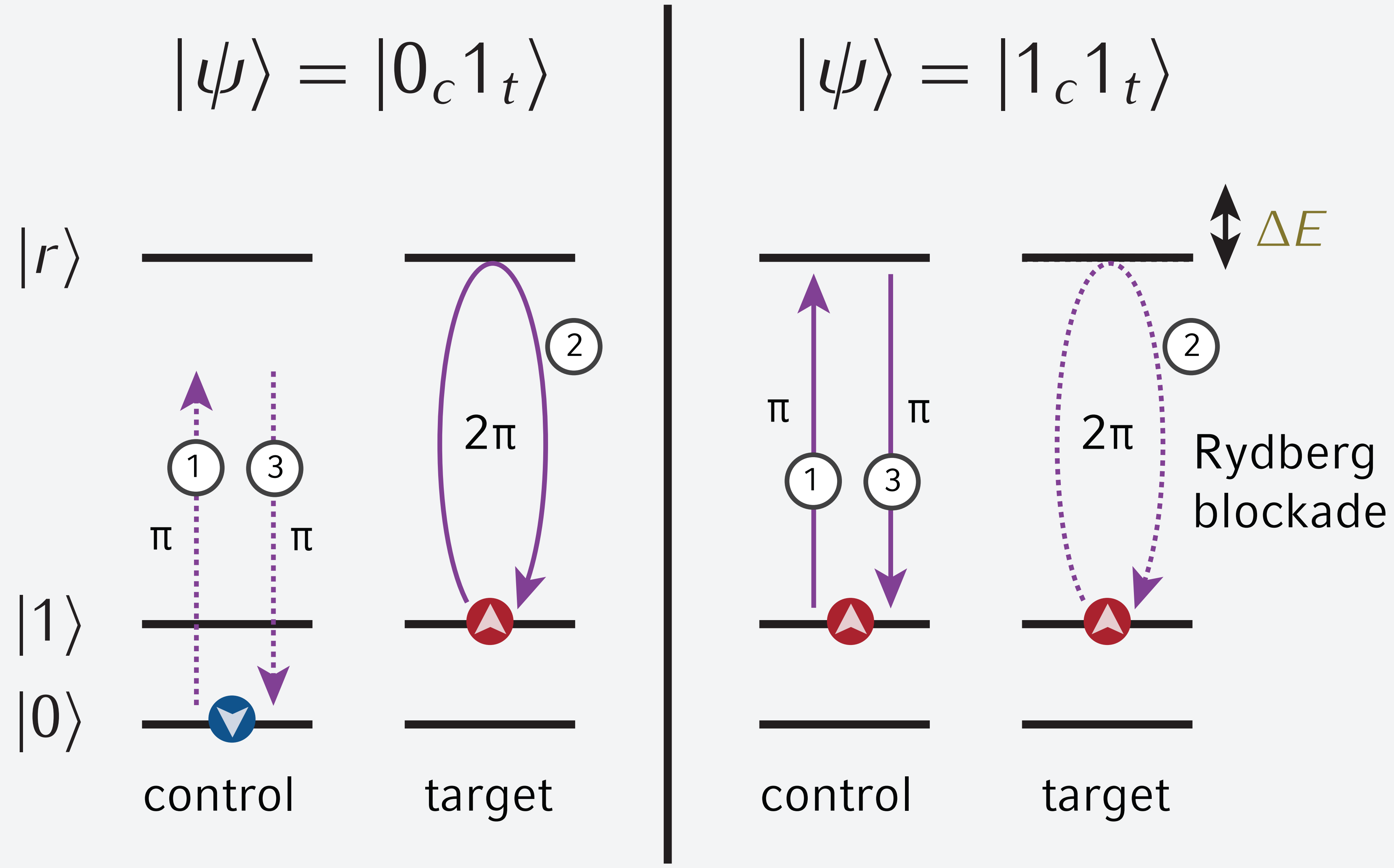


Two atom separation

Blockade Regime $\Delta E \gg \Omega$

→ cannot excite two atoms at close distance

Sequential pulses



E. Urban et al., Nat. Phys. **5**, 110 (2009)