Quantum information processing and simulation with Rydberg atom arrays (tweezer arrays)

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Overview:

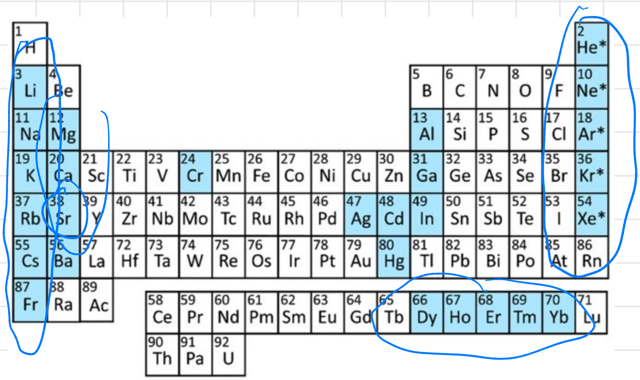
I Single atoms as quantum building blocks

II Rydberg interactions + QIP

III Simulation + Research @ UChicago

I

1. atom?



- typ.: atom with $1e^-$

  e.g. Rb "silicon of atoms"

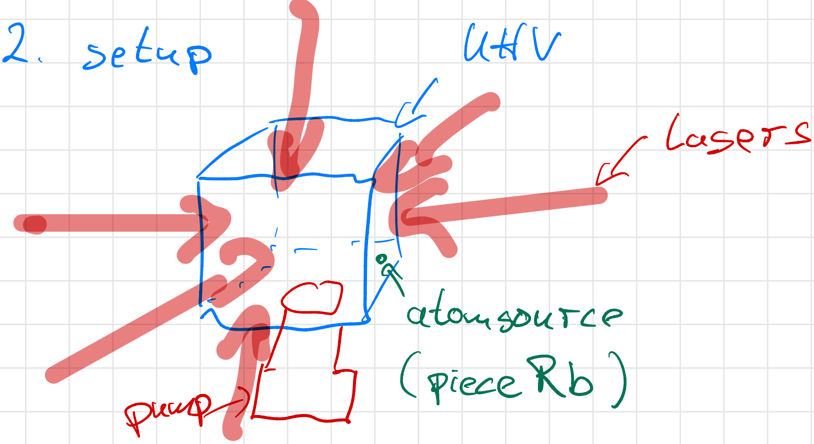
- also atom with $2e$

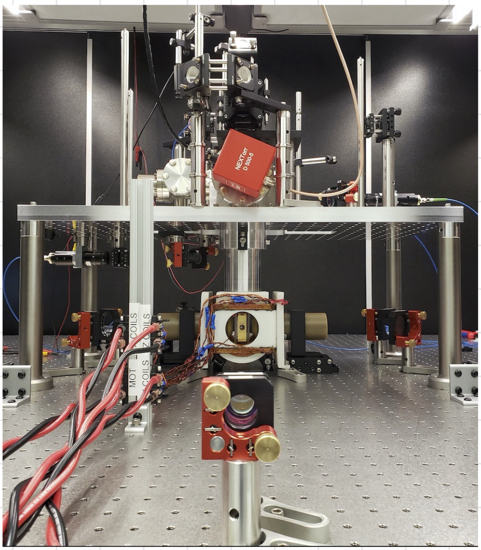
  e.g. Sr, Yb

opportunities:
- optical clocks
- nuclear spin

2

2. setup





- Vacuum tech
- Lasers, optics
- MW sources
- photo detectors

3 cooling

atom @ RT $\vec{v} \sim 300 \frac{m}{s}$

- moving atom sees doppler shift

  => absorbs from counter prop. beam

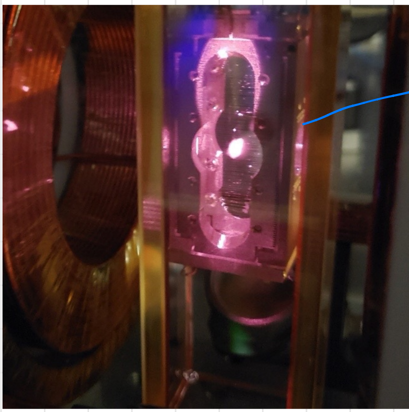
$$\vec{P}_{atom} = m\vec{v} - \hbar\vec{k}_{abs} + \hbar\vec{k}_{emit}$$

$$\langle k_{emit} \rangle = 0$$

$\Rightarrow$ atom slowed down

$+ \vec{B}$-fields $\Rightarrow$ spatially dep. restoring force

Magneto Optical Trap : MOT

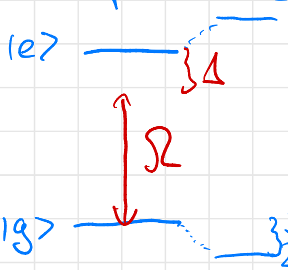


10^9 atoms

$T \sim 10\mu k$, $v \sim \frac{cm}{s}$

4. trapping single atoms

- optical trap



$$\hat{H}_{/\hbar} = \begin{pmatrix} 0 & \frac{\Omega}{2} \\ \frac{\Omega}{2} & \Delta \end{pmatrix}$$

diag. $\Rightarrow$ $\Delta \gg \Omega$

$$\tilde{E}_g = -\frac{\Omega^2}{4\Delta} \qquad \tilde{E}_e = \Delta + \frac{\Omega^2}{4\Delta}$$

"Light shift" AC-Stark

$$U = \frac{\Omega^2}{4\Delta} = \frac{|Ed|^2}{4\Delta} \propto \text{Laser intensity}$$

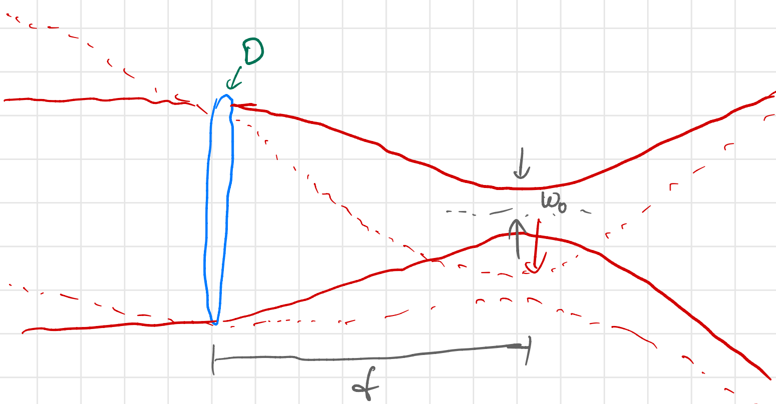
- $\omega_{Laser} < \omega_{atom}$ "red detuned"

  ⇒ atom is attracted to high I

- $\omega_{Laser} > \omega_a$ "blue detuned"

  ⇒ atom repelled

⇒ <u>Optical tweezers</u> (red detuned, focused beam)



$w_0 \approx \frac{2f\lambda}{\pi D}$

want w_0 small ⇒ $\frac{D}{f}$ large

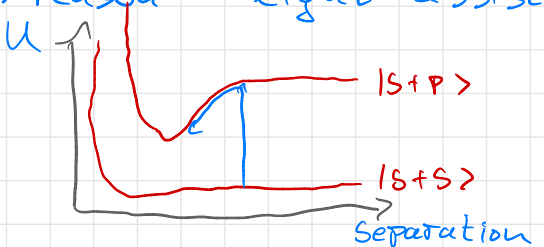
⇒ microscope objective $(NA = \frac{D}{2f})$

typ $NA \sim 0.6$; $\lambda \sim 810nm$ (Rb)

⇒ $w_0 \sim 400nm$

- how many atoms? ⇒ 0 or 1 when trap light

⇒ reason: light assisted collisions



⇒ 2 atoms get kicked out

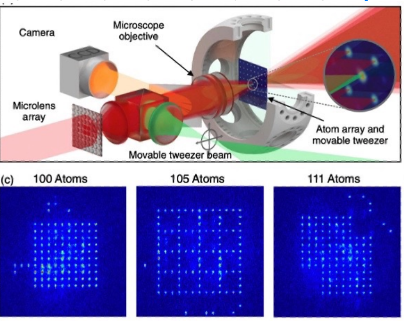
⇒ trap occupied typ with 50%

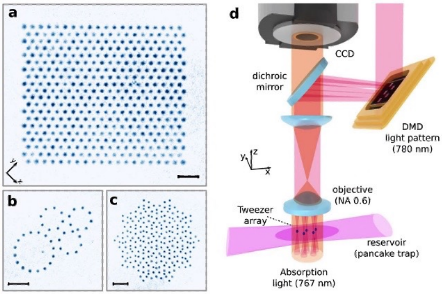
Arrays of optical tweezers:

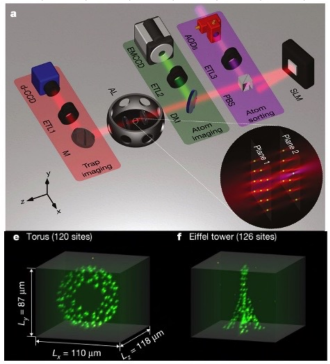
- multiple input beams @ different angles

⇒ multipli foci

⇒ many different ways







Birkl group: Defect-Free Assembly of 2D Clusters of More Than 100 Single-Atom Quantum Systems, PRL 122, 203601 (2019)

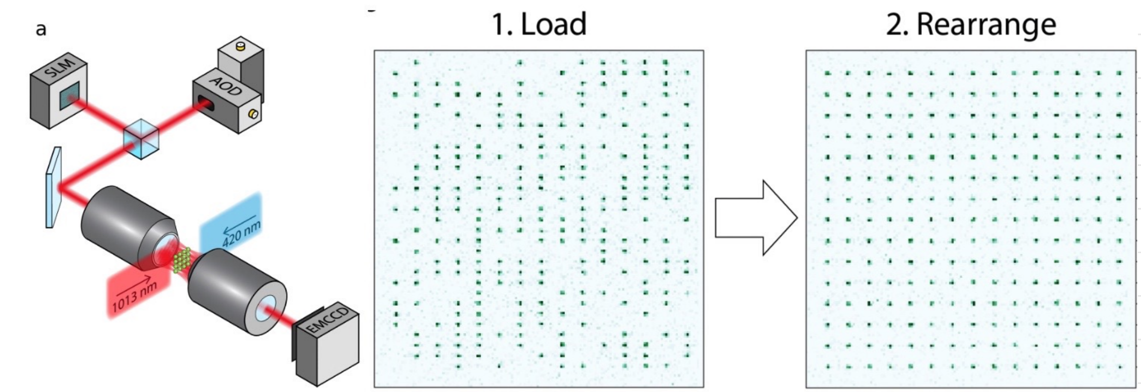
Whitlock group: Preparation of hundreds of microscopic atomic ensembles in optical tweezer arrays; NPJ quantum (2020)

Browaeys group: Synthetic three-dimensional atomic structures assembled atom by atom; Nature 2018

5. need rearrangement of prob. loaded atoms

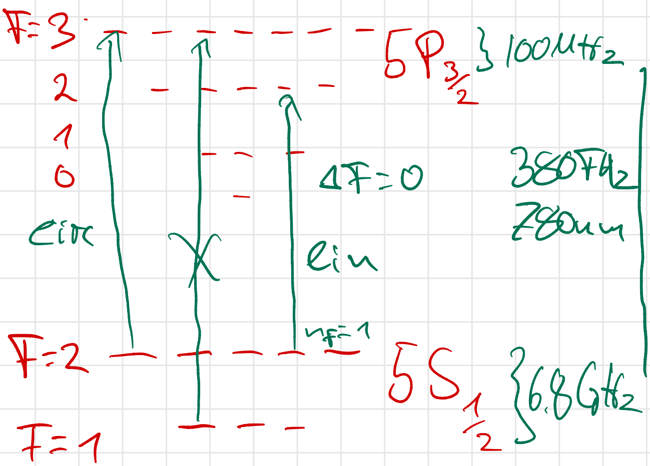
1. load prob. atoms
2. take pic. identify loaded / empty trap
3. move loaded atoms on desired empty trap sites
4. take pic

⇒ 2016 Lukin, Browaeys, Ahn



Lukin group: Quantum phases of matter on a 256-atom programmable quantum simulator; Nature 2021

6. 1 Atom = 1 qubit



optical sel. rules

light-atom exchange angular momentum

$\Delta L = \pm 1$; Δl_z = photon pol

0 lin

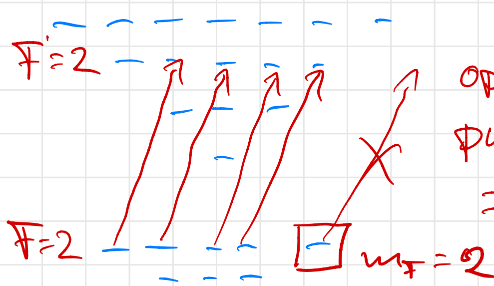
± 1 circ

$\Rightarrow$ translation HF basis

$\Delta L = \pm 1$, $\Delta F = 0, \pm 1$, Δm_F = pol

but not $\Delta F = 0$ with $m_F = 0 \to 0$

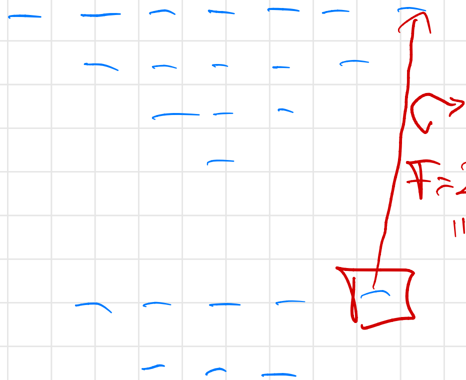
a) initialization



optically pump

$\Rightarrow F=2\ m_F=2$

b) measurements

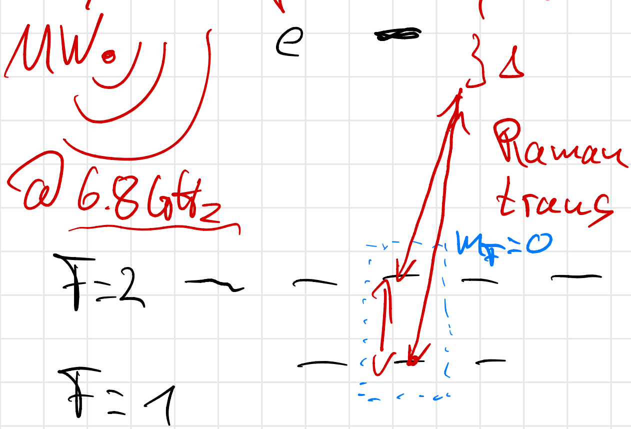


$F=2 \to F'=3$
"cycling trans"
collect many photons

- in reality very challenging

$\Rightarrow$ solution ① state dependent loss
② fluorescence image

c) manipulate qubit states

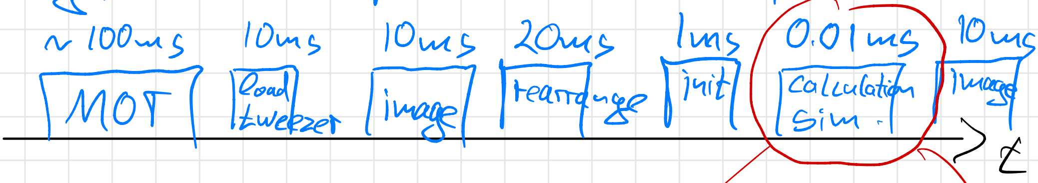


$|F=2, m_F=0\rangle := |1\rangle$
$|F=1, m_F=0\rangle := |0\rangle$

- mag. unsensitive

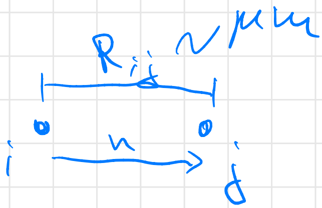
$\Rightarrow$ long coherence
$\sim 10\,s$

7. typical experiment sequence



200 ms

Lecture II Rydberg Int.



spin-spin int $\ll H_2$

- electric dip.-dip. Int:

$$\hat{V} = \frac{1}{4\pi\varepsilon_0} \frac{\vec{d}_i \vec{d}_j - 3(\vec{d}_i \vec{n})(\vec{d}_j \vec{n})}{R_{ij}^3}$$

- symmetric atom $\langle \vec{d}_i \rangle = 0$

  but $\langle a | d_i | b \rangle \neq 0$: transition dip element

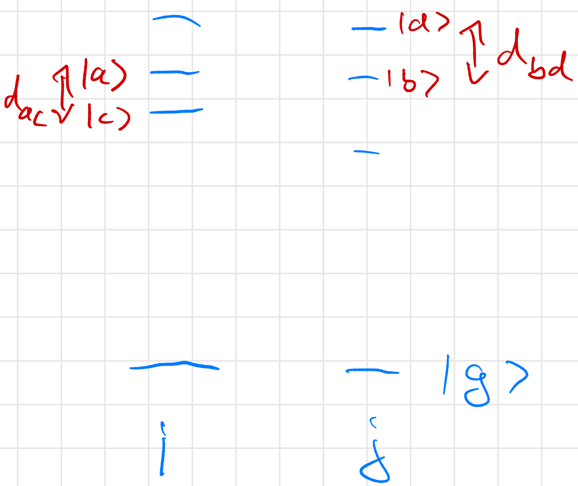
- for low trans: e.g. $5S \Leftrightarrow 5P$

  d_{ab} too small + 5P state decays fast

- Rydberg states: states with high n

$d_{NN'} \propto N^2$: huge + long lived
$(\tau \sim N^3)$

$\Rightarrow$ strong dipolar int.



$\Rightarrow$ two atom states

$$\Delta = (E_a + E_b) - (E_c + E_d)$$

$$\hat{H} = \frac{V_{ij}}{2} |ab\rangle\langle cd| + h.c.$$

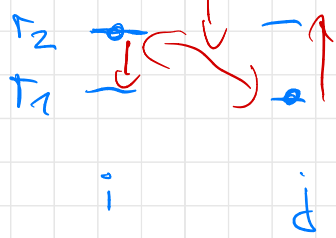
- approx : (1) only consider states with Δ small
  (2) neclect angular dep

$$\hat{H} = \left[\frac{d_{ac} d_{bd}}{2 R^3} |ab\rangle\langle cd| + h.c. \right] + \Delta |cd\rangle\langle cd|$$

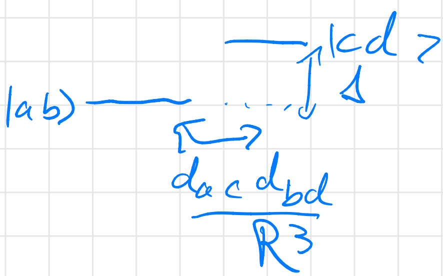
Förster defect

(a) Res. interactions $\Delta = 0$

$$\Rightarrow \quad \hat{H} = \frac{d_{ac} d_{bd}}{2R^3} |ab\rangle\langle cd| + h.c.$$



(b) non-res. int.



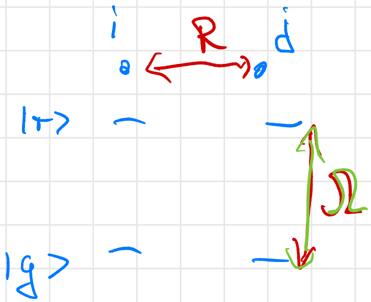
$$\Rightarrow \text{ pertubation } \quad E_{ab} \to E_{ab} + \frac{|d_{ac}|^2 |d_{bd}|^2}{R^6 \Delta}$$

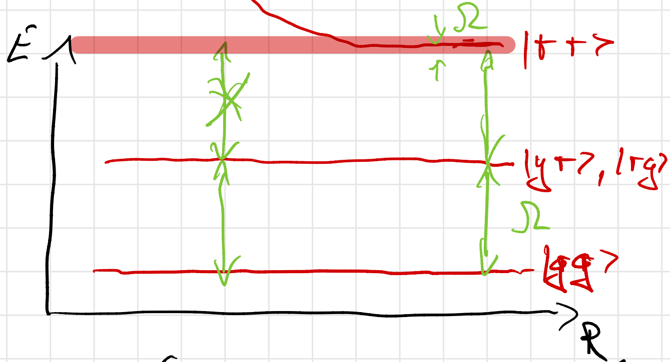
$$\hat{H} = \frac{C_6}{R^6} |ab\rangle\langle ab| \quad ; \quad C_6 = \frac{|d_{ac}|^2 |d_{bd}|^2}{\Delta}$$

$\Rightarrow$ typ for atoms coupled to same Ryd. state

- C_6 is huge : e.g. Rb 80S $\Rightarrow C_6 = \frac{4\,THz}{\mu m^6}$
  @ $5\mu m \Rightarrow 250\,MHz$

• useful? ⇒ Rydberg blockade





$$V_{ij}(R_b) = \Omega \Leftrightarrow \frac{C_6}{R_b^6} = \Omega \Leftrightarrow R_b = \left(\frac{C_6}{\Omega}\right)^{\frac{1}{6}}$$

• couple two atoms with $R < R_b$ to $|r\rangle$

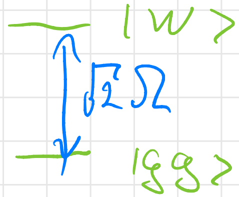
$$\hat{H} = \frac{\hbar}{2} \sum_{i,j} \Omega\left(|r_i\rangle\langle g_i| + |g_i\rangle\langle r_i|\right) + V_{ij}\,|rr\rangle\langle rr|$$

Ryd. blockade ⇒ $\hat{P} = \mathbb{1} - |rr\rangle\langle rr|$

$$P\hat{H}P = \frac{\hbar\Omega}{2}\boxed{\sqrt{2}}\left(|W\rangle\langle gg| + h.c.\right)$$

$$|W\rangle = \frac{1}{\sqrt{2}}\left(|gr\rangle + |rg\rangle\right)$$

• 2 blockaded atoms form 1 TLS

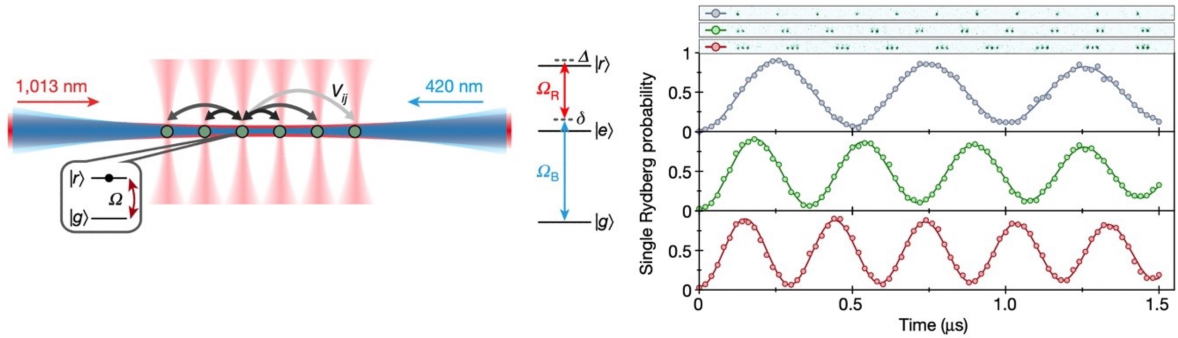


"super atom"

• general : N blockaded atoms

⇒ 1 TLS ; $|W\rangle = \frac{1}{\sqrt{N}} \sum_i |g_1 \ldots r_i \ldots g_N\rangle$

$\tilde{\Omega} = \sqrt{N}\,\Omega$



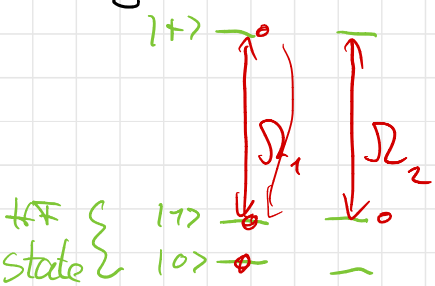
Probing many-body dynamics on a 51-atom quantum simulator; Bernien, Lukin group Nature (2017)

• simple π pulse ⇒ entanglement

e.g. Endres group : F > 99%

4. 2-qubit gates: many options

• Jaksch et al. PRL 2000

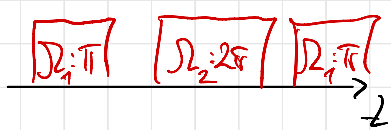


• 2 atoms blockade

• Ω couples $|1\rangle \Leftrightarrow |r\rangle$

• not $|0\rangle$

protocol : 3 pulses

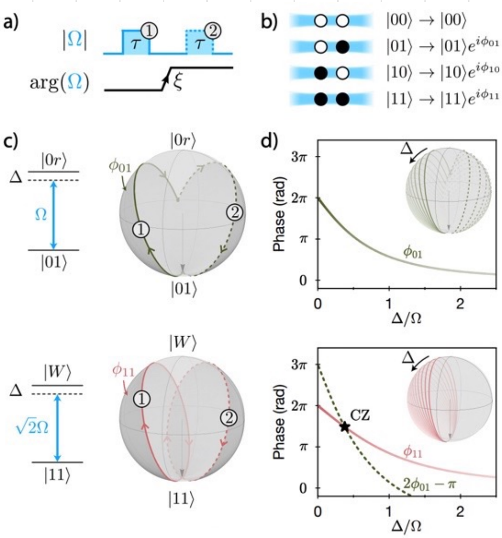


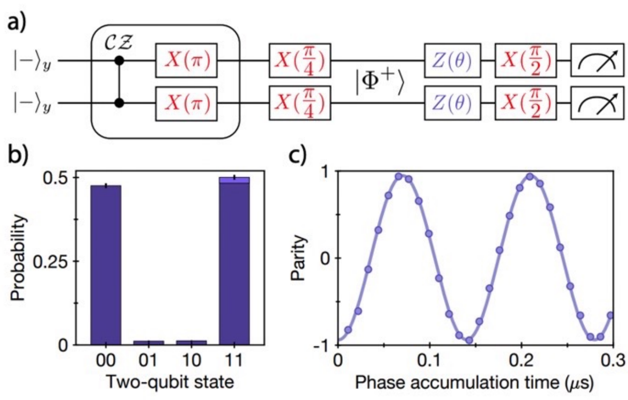
in	out
$\|00\rangle$	$\|00\rangle$
$\|01\rangle$	$-\|01\rangle$
$\|10\rangle$	$-\|10\rangle$
$\|11\rangle$	$-\|11\rangle$ blockade

$\Rightarrow$ CZ gate

- CZ symmetric, pulses not
- atom 1 spends time in $|r\rangle$
- $F \sim 89\%$

better gates: Pichler/Levine gate: PRL 2019





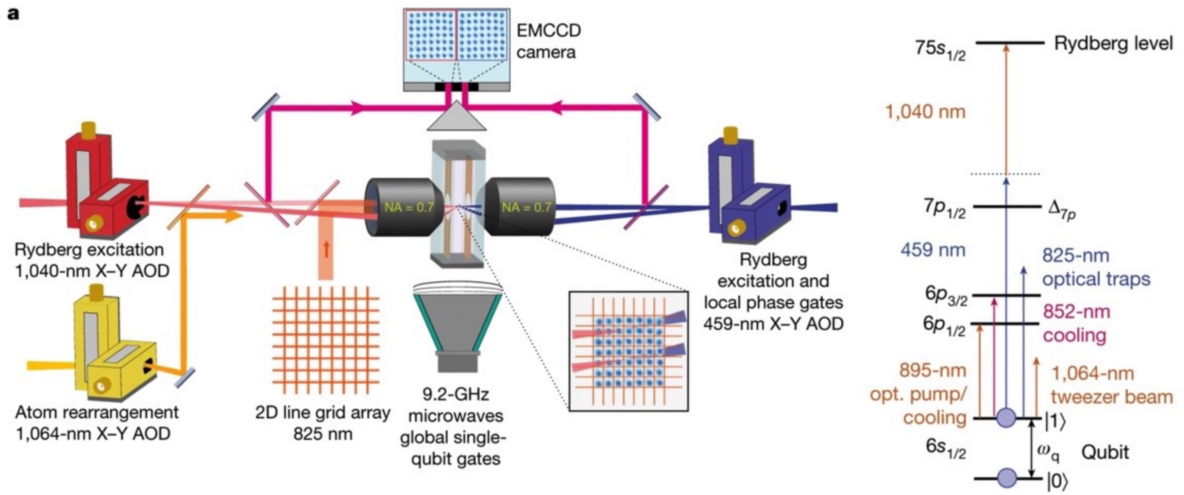
Parallel implementation of high-fidelity multiqubit gates with neutral atoms. Levine (Lukin group) PRL 2019

- $\sim 97.5\%$ F

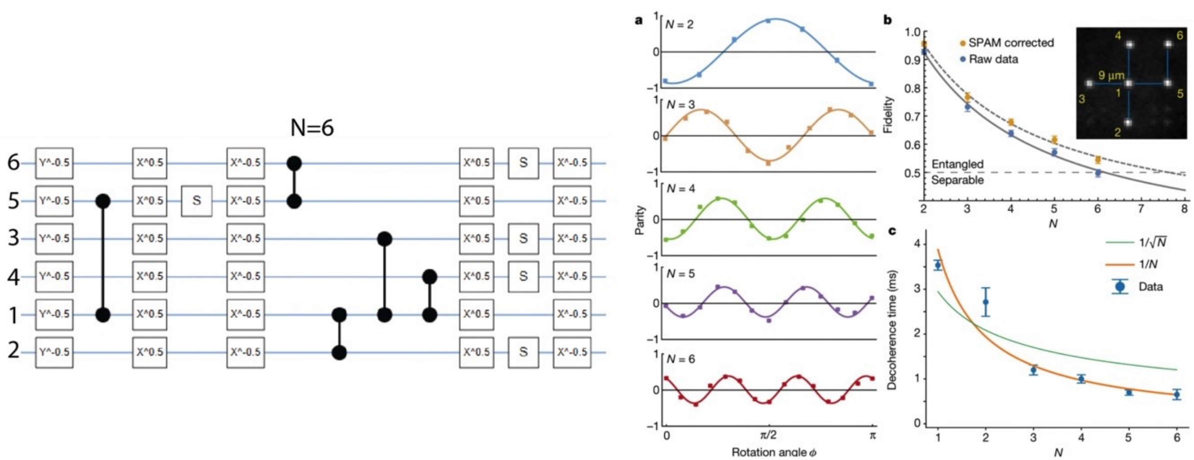
$\Rightarrow$ universal gate set

⇒ quantum computer?

- put it all together
- requirement: individual addressing
  ↳ multiple options

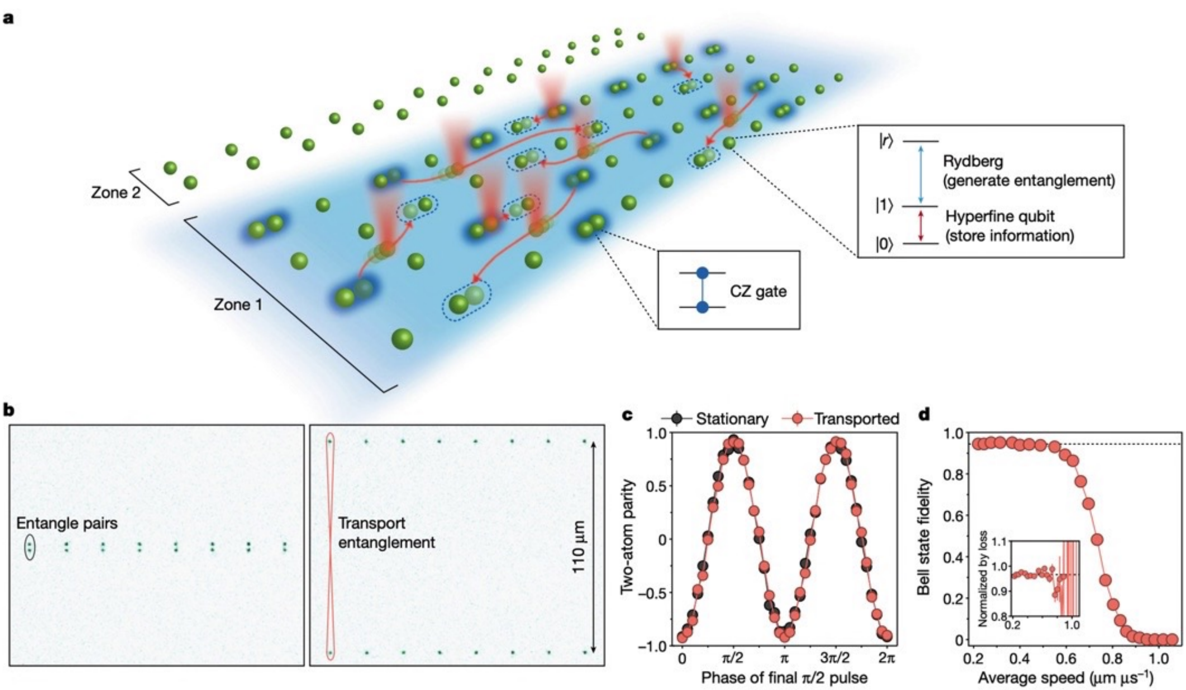


Saffman group: Multi-qubit entanglement and algorithms on a neutral-atom quantum computer. Nature 2022

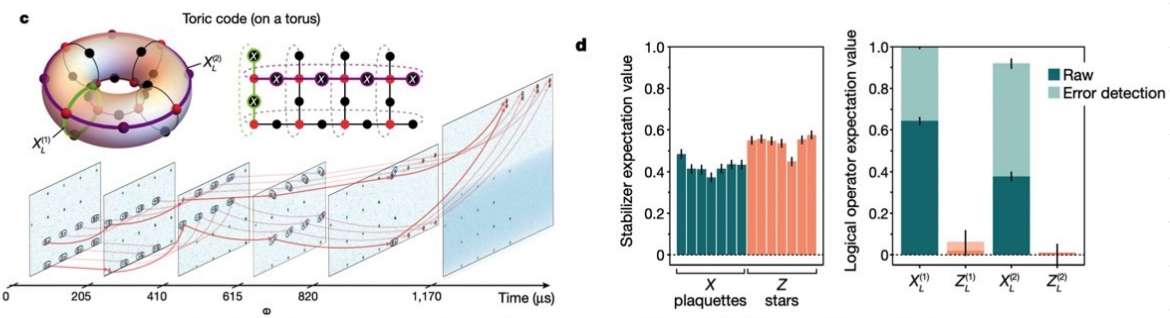


Saffman group: Multi-qubit entanglement and algorithms on a neutral-atom quantum computer. Nature 2022

b) coherent transport of atoms



A quantum processor based on coherent transport of entangled atom arrays. Bluvstein (Lukin group) Nature 2022



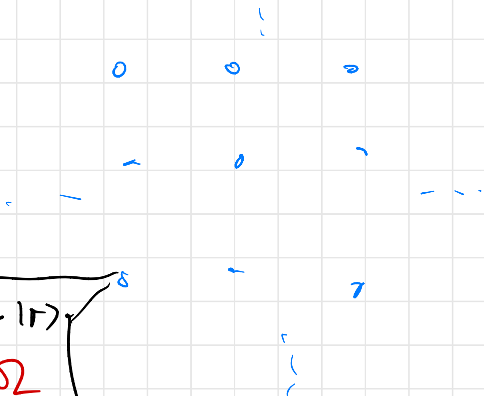
A quantum processor based on coherent transport of entangled atom arrays. Bluvstein (Lukin group) Nature 2022

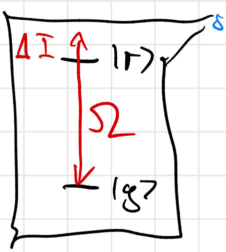
remarks:

- F need to improve
- better read out needed

III Quantum Sim.

1. Hamiltonians:





$$\frac{\hat{H}}{\hbar} = \sum_i \frac{\Omega}{2} \sigma_x^i - \Delta \hat{n}^i + \sum V_{ij} \hat{n}_i \hat{n}_j$$

$$\sigma_x = |g\rangle\langle r| + |r\rangle\langle r| \quad , \quad \hat{n} = |r\rangle\langle r|$$

$$\hat{n} = \frac{1}{2}(\mathbb{1} - \sigma_z)$$

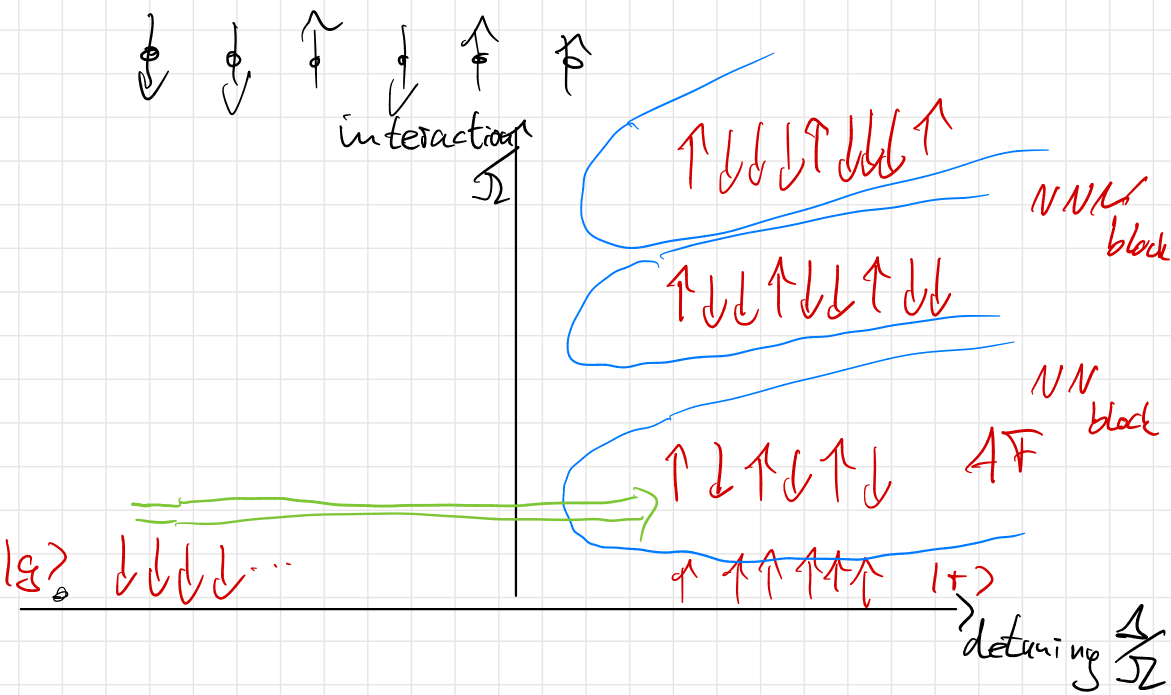
$$\Rightarrow \frac{\hat{H}}{\hbar} = \frac{\Omega}{2} \sum \sigma_x^i + \sum (\Delta + B_i) \sigma_z^i + \frac{1}{4} \sum V_{ij} \sigma_z^i \sigma_z^j$$

$B_i = \sum_j V_{ij}$ $\Rightarrow$ transverse Ising

$|g\rangle = |\downarrow\rangle \qquad |r\rangle = |\uparrow\rangle$

- highly tunable:
  - V_{ij} rearrangement
  - Ω : laser power
  - Δ : –"– detuning
- Ω, Δ can be $\Omega(t)$ $\Delta(t)$
- –"– can be $\Omega_i(t)$, $\Delta_i(t)$

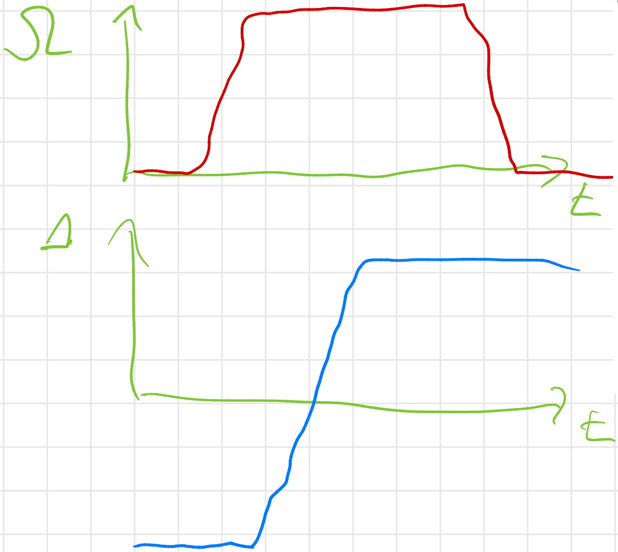
phase diagram 1D

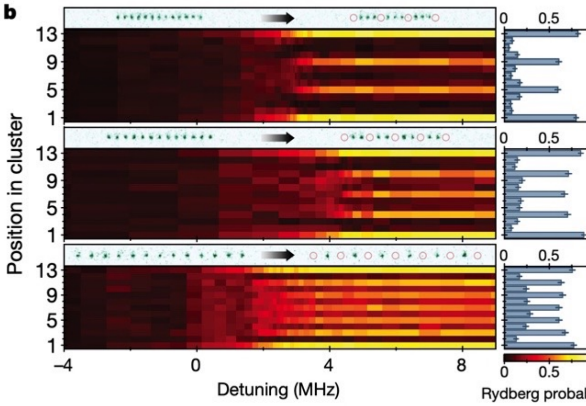


- prepare:
  1. arrange in desired geometry

2. initialize $\downarrow\downarrow\downarrow\downarrow$

3. Rydberg laser





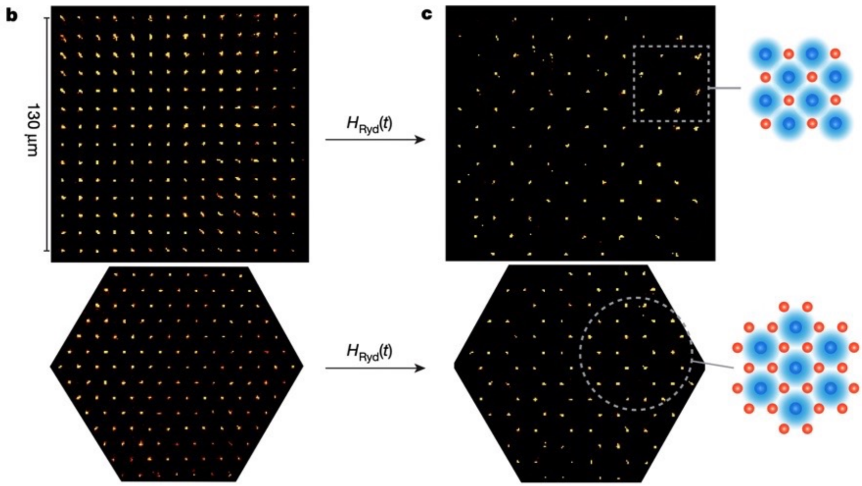
- If slow enough
$\Rightarrow$ adiabatically prepare phase

4. measure

$\Rightarrow$ study PT, study non equilib. dyn.
(e.g. Kibble Zurek
quench dynamics)

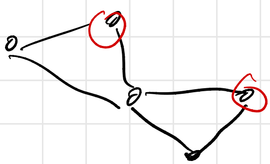
- entanglement generation
$|\downarrow\uparrow\downarrow\uparrow\ldots\rangle + |\uparrow\downarrow\uparrow\downarrow\ldots\rangle$ Omran Science 2019

2D



Quantum simulation of 2D antiferromagnets with hundreds of Rydberg atoms. Scholl (Browaeys group) Nature 2021

- beyond square:
  - e.g. • triangular: frustation
  - • kagome
- recent highlight: topological spin liquid
  - ⇒ Semeghini Science 2021
- connection to optimization problems
  - • Maximum indepedent set
    - ⇒ NP-hard



Pichler arxiv 2018

2. Spin exchange $\hat{H}$

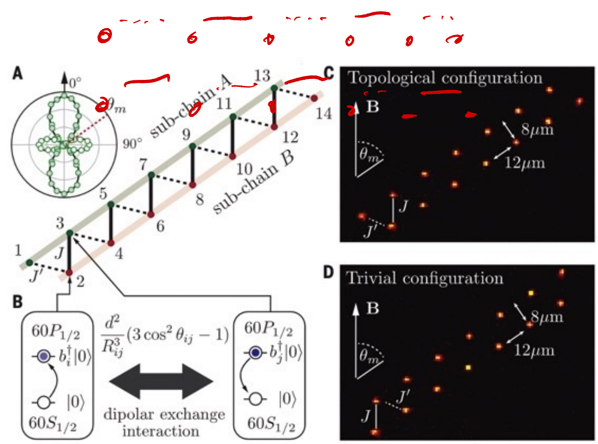
P —   p: ↑

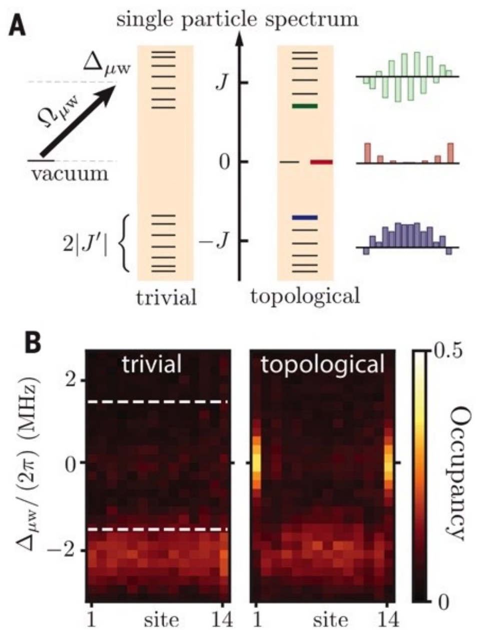
S —   s: ↓

$$V_{dd} = \frac{C_3}{R^3} |S_i P_j\rangle\langle P_i S_j| + h.c.$$

$$\Rightarrow \hat{H}_{XY} = \sum_{i,j} \frac{C_3}{R_{ij}^3}\left(\sigma_+^i \sigma_-^j + \sigma_-^i \sigma_+^j\right)$$

- XY spin model
- $\hat{=}$ transport of hardcore bosons
- challenge: prepare 2 rydberg states





Observation of a symmetry-protected topological phase of interacting bosons with Rydberg atoms. Browaeys group Science 2019

- remarks:
  - more H possible by Floquet engineering e.g. XXZ spin H (Browaeys/Weidemüller PRX q. 2022)
  - possibility to include tunneling (Kaufman + Bakr arxiv 2022)
  - sooon > 1000 atoms