Pasqal Defining the quantum reality

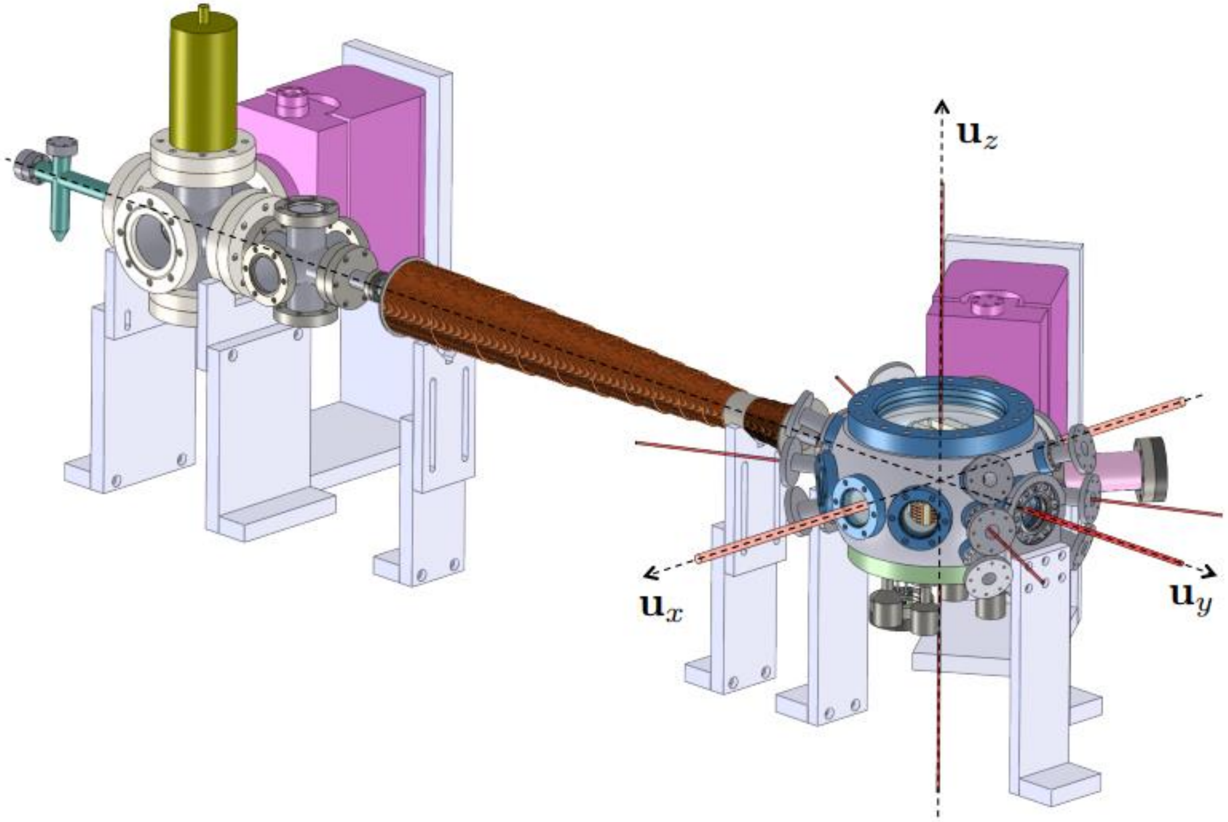
Lecture 2: Atomic qubits

December 17, 2025

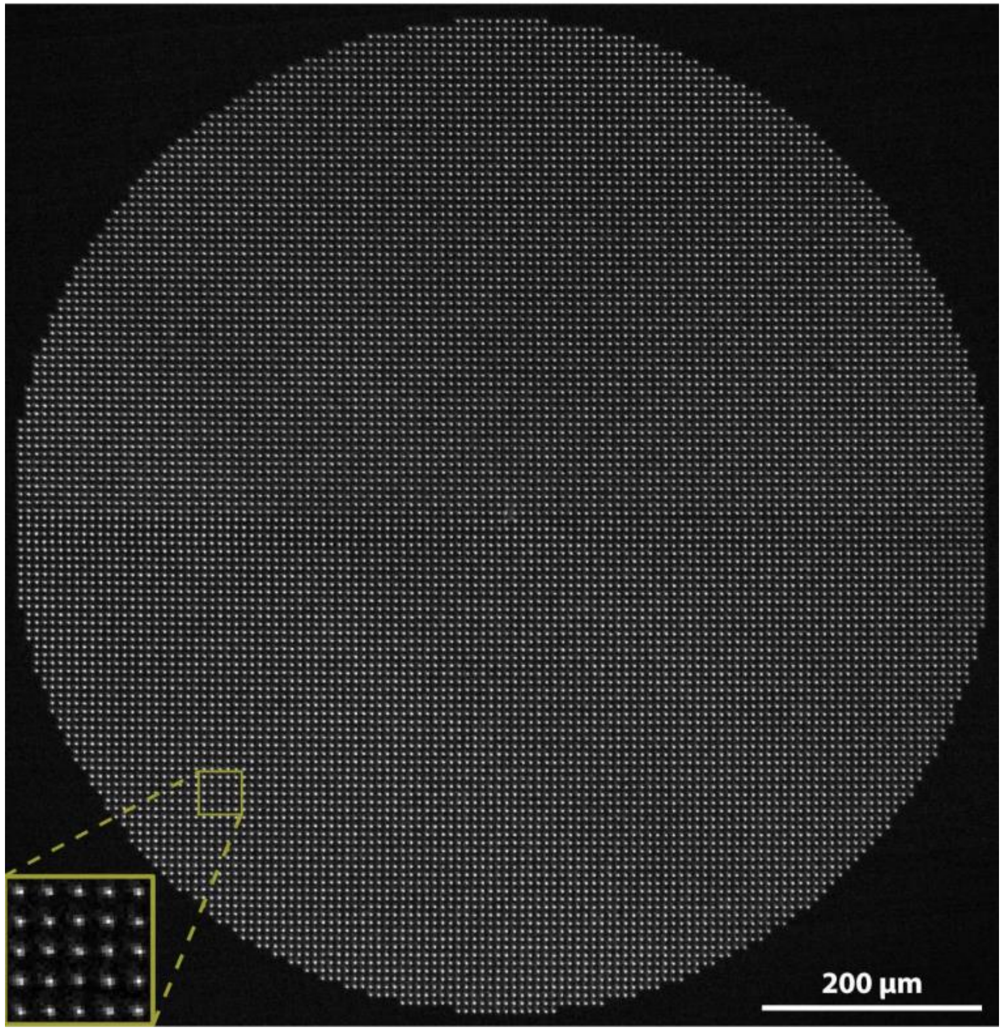
Pasqal

Trapping neutral atoms

Pasqal

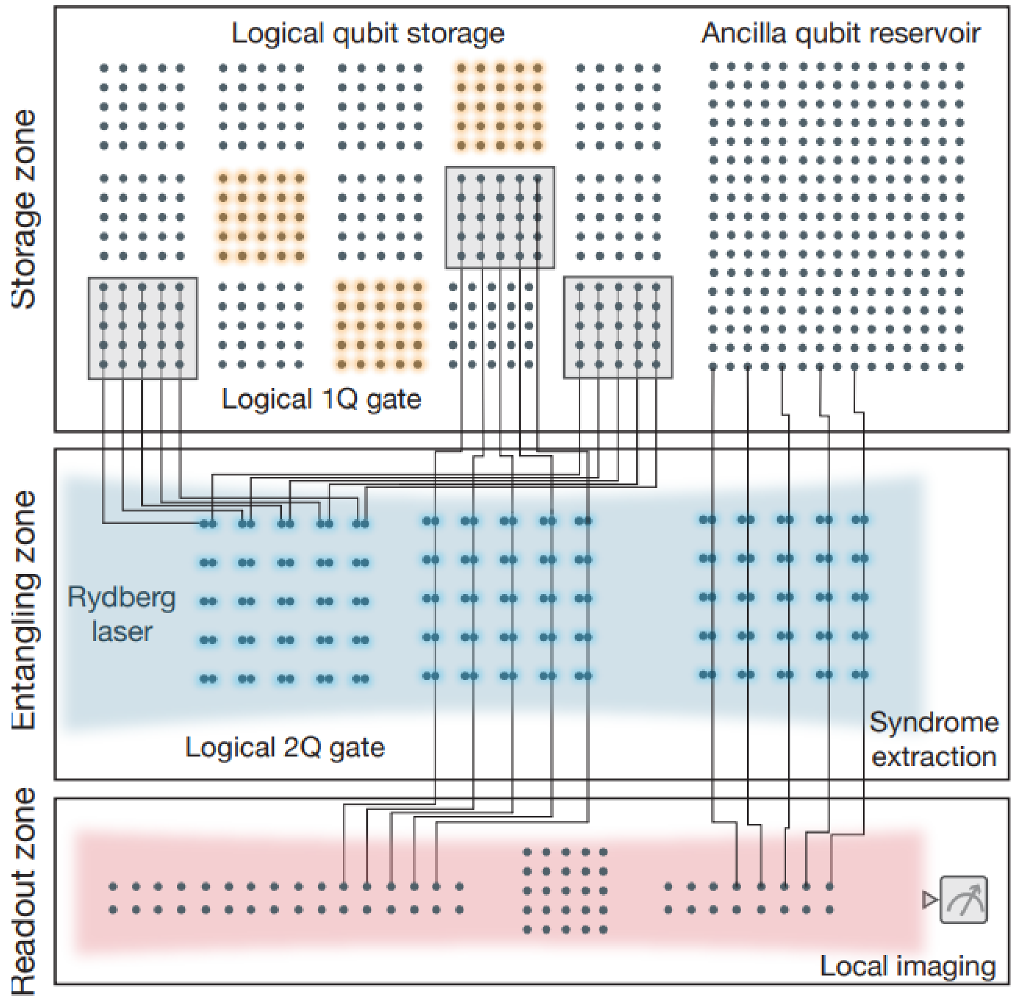


~ 12000 trapped atoms

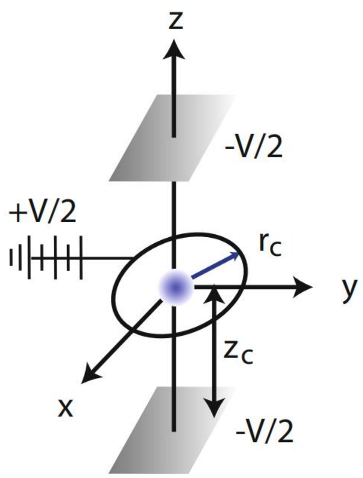


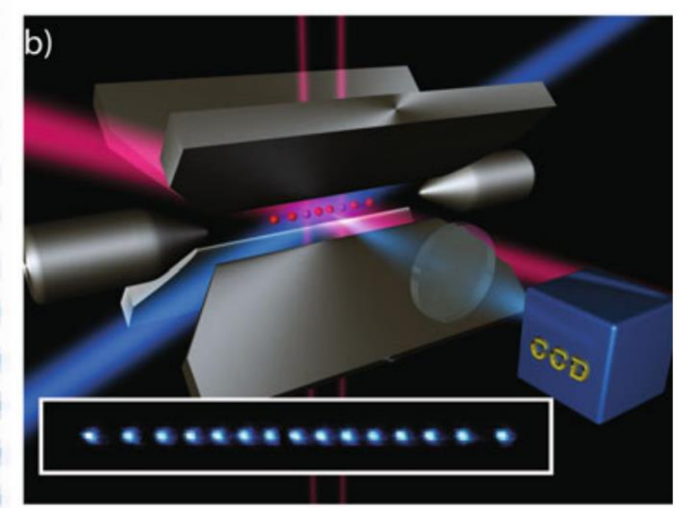
Trapping neutral atoms

Pasqal



Trapping ions





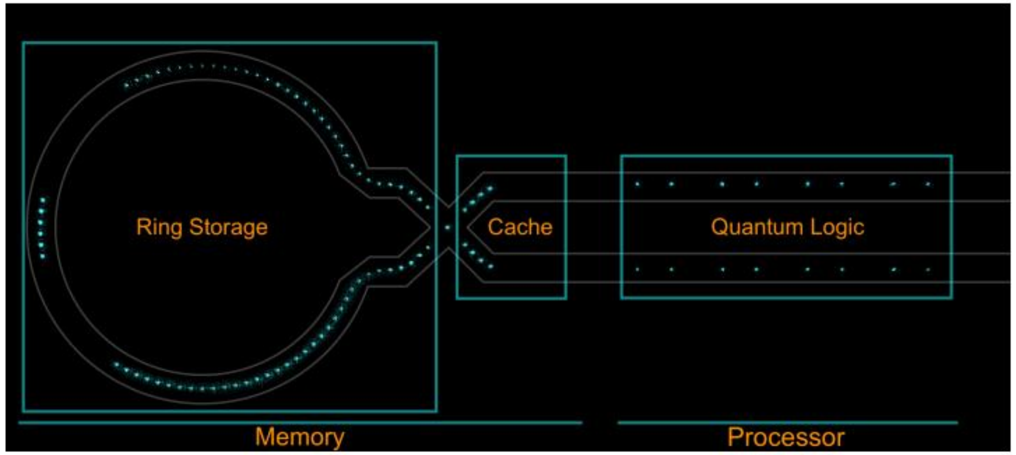


FIG. 1. An image of 98 atomic ions illuminated by resonant laser light in the Helios 2D surface trap illustrated in Fig. 2. The overlaid lines indicate different regions of the device with the quincunx of ions showing the location of the ion trap junction.

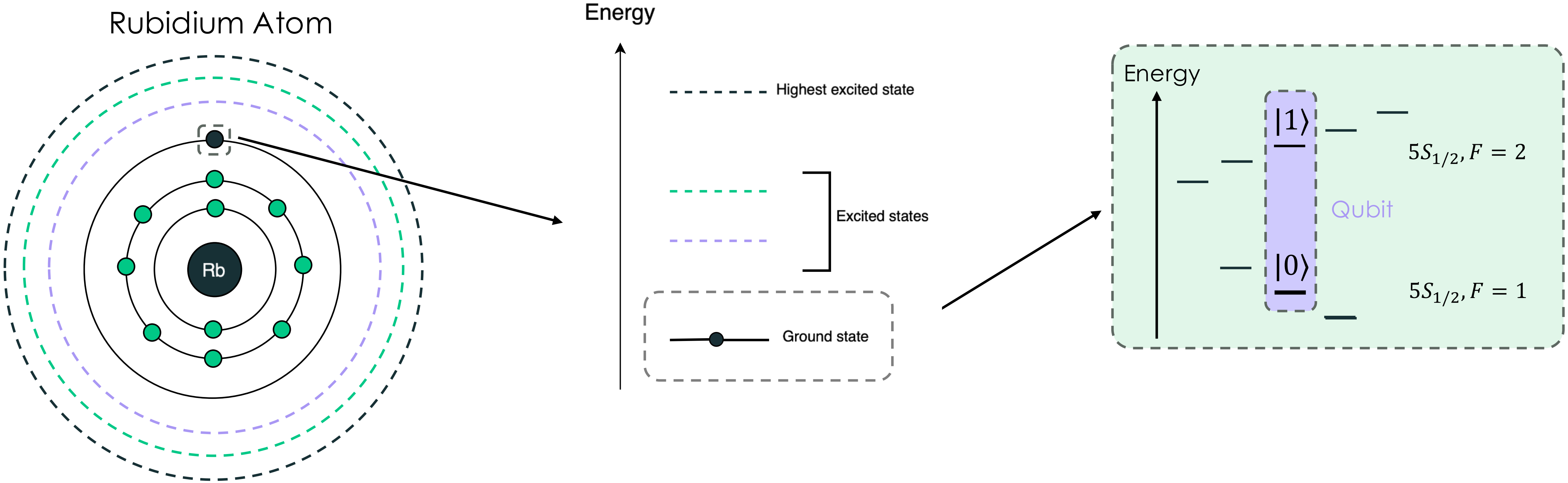
Atomic species choice

1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	57 La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	89 Ac	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt									

58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

Atomic states and qubit encoding

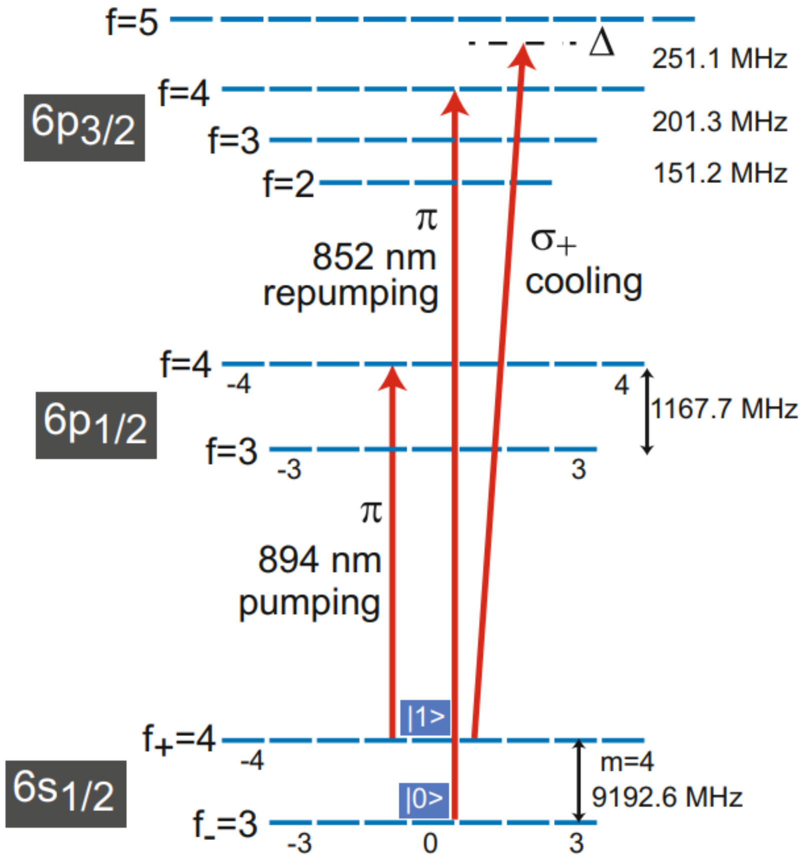
Pasqal



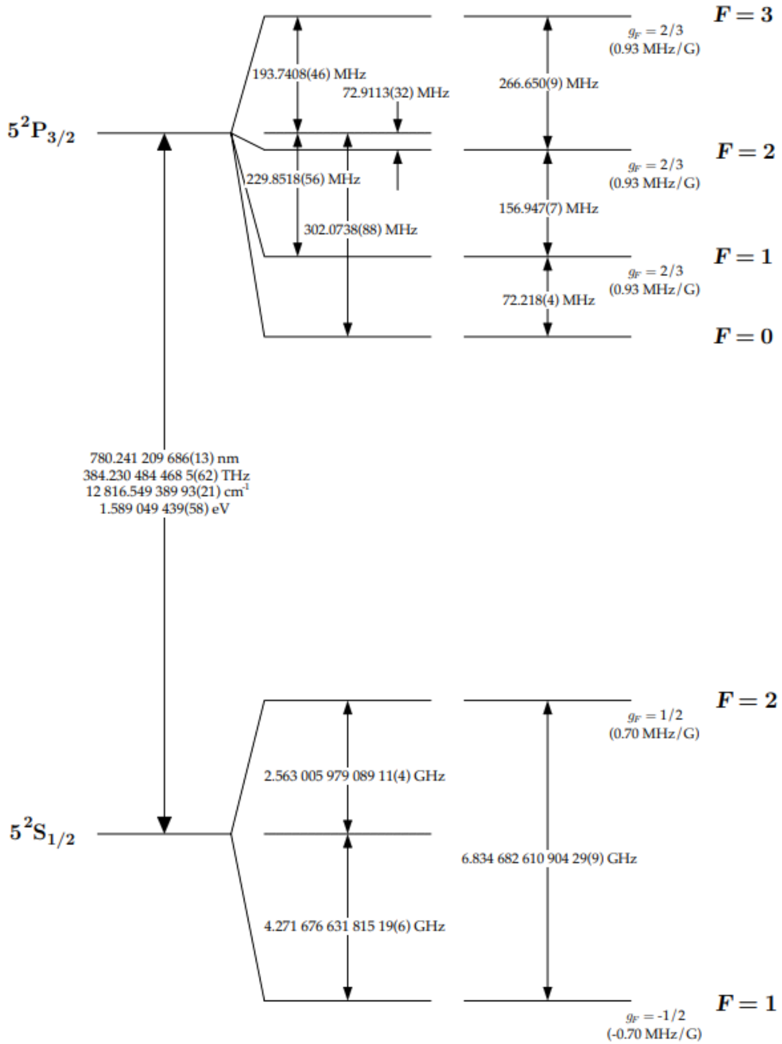
Energy levels and qubit

Pasqal

Cesium

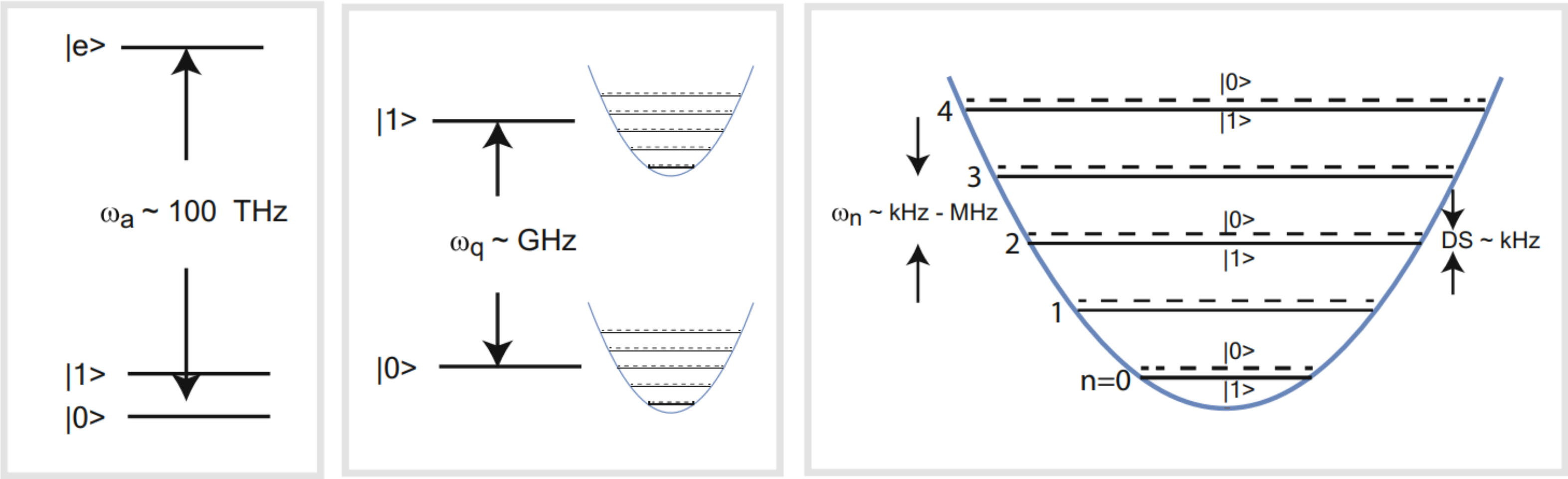


Rubidium

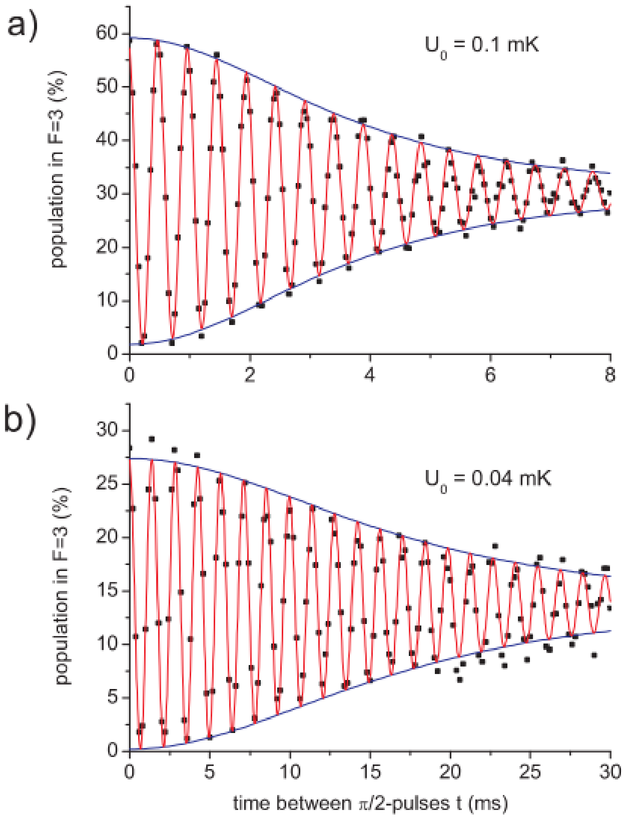


Motional dephasing

Pasqal

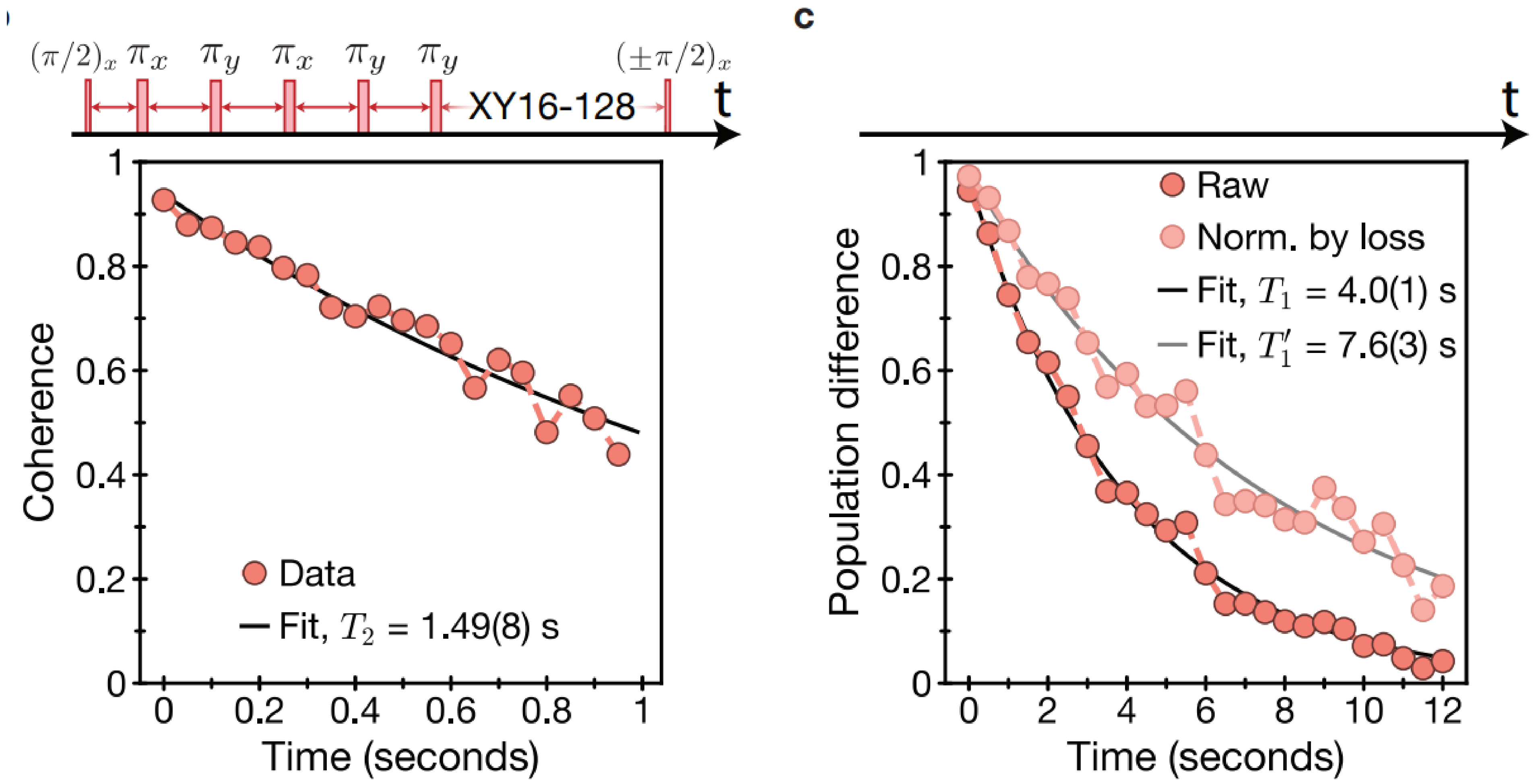


Ramsey experiment:

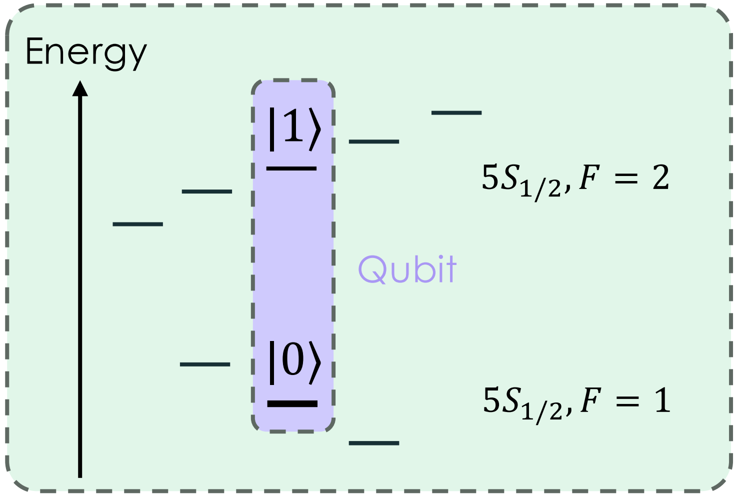


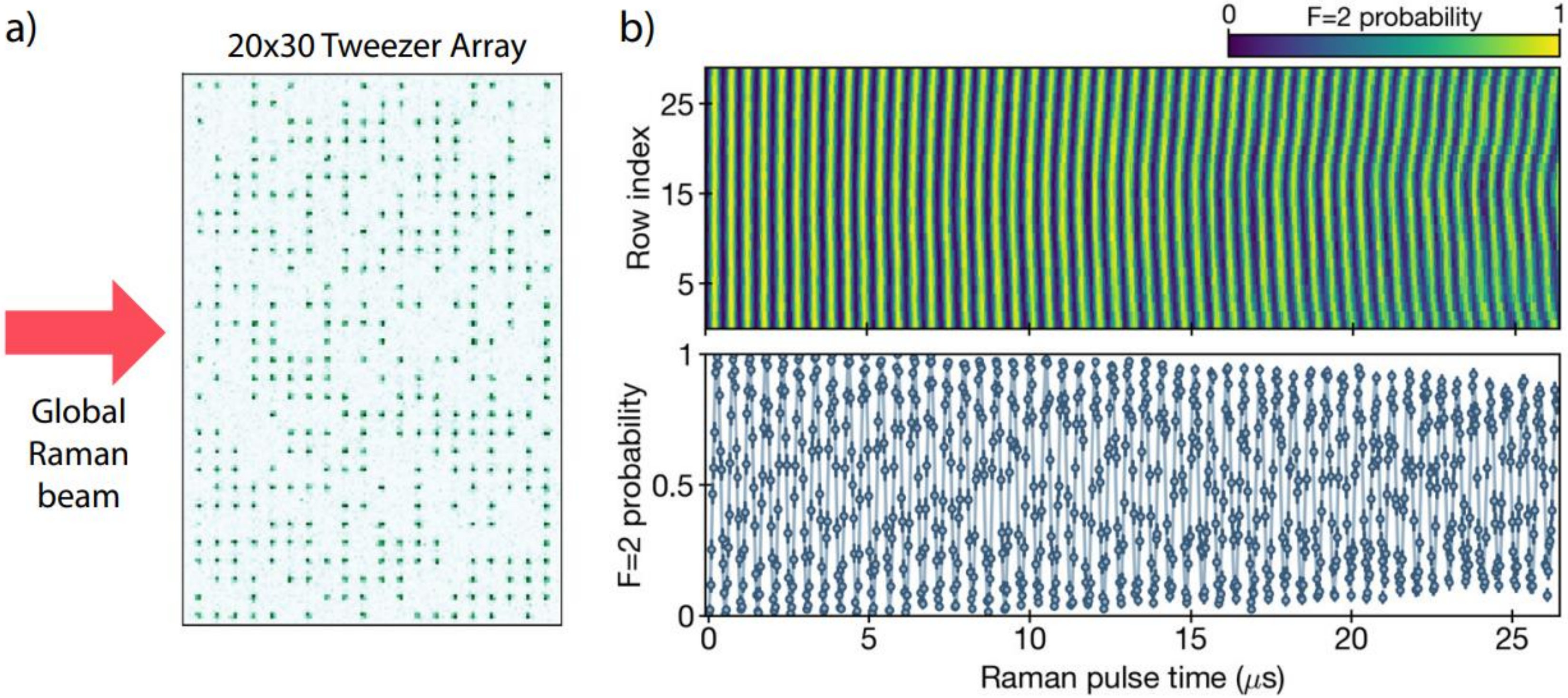
T_1 and T_2 times

Pasqal



Rabi oscillations



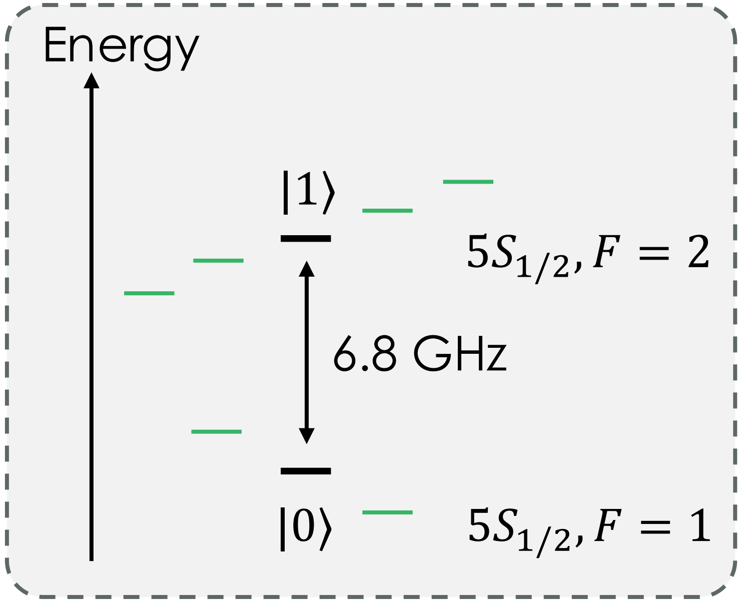


Atomic states and qubit encoding

Pasqal

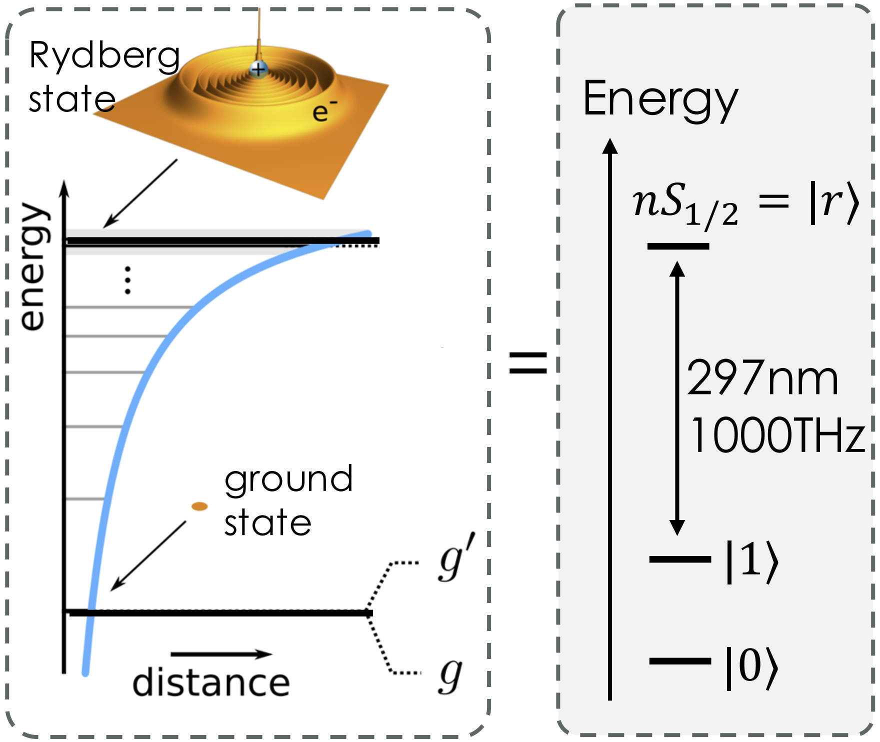
Long-lived ground states

- Equivalent of the qubit used in Rubidium to define the second → very well known
- Strongly insensitive to environment → long lifetime and coherence time

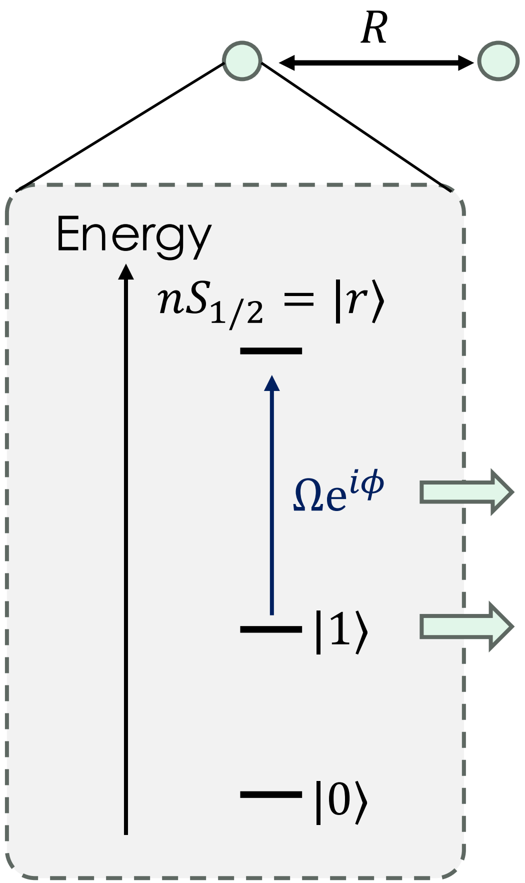


Entanglement through Rydberg states

- Rydberg atoms behave as a dipole: strongly interacting
- Long lifetime (compared to interaction)



Two-qubit gate through Rydberg interactions



Interaction Hamiltonian between two atoms:

$$H = \hbar\Omega(\sigma_1^x + \sigma_2^x) + \frac{C_6}{R^6} n_1 n_2$$

These are the lasers which connect $|1\rangle$ to $|r\rangle$

This is the energy shift due to Rydberg interactions

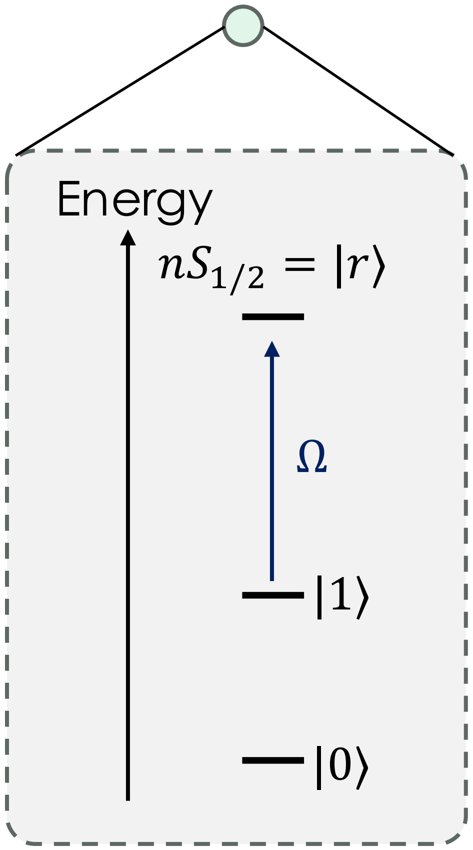
420nm + 1013nm lasers

Only $|1\rangle$ is coupled to Rydberg states

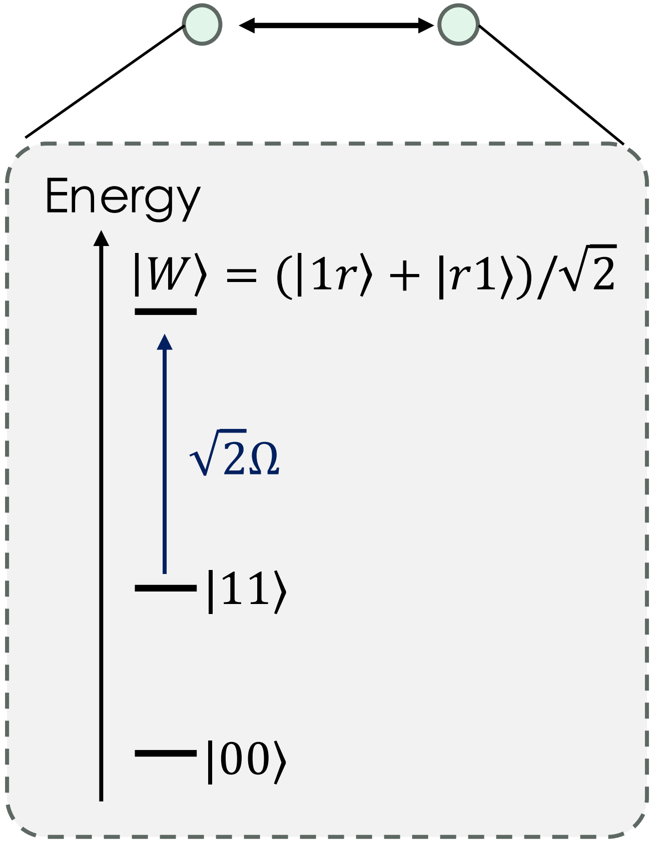
Two-qubit gate through Rydberg interactions

Pasqal

Single atom



Two atoms in the **Rydberg blockaded** regime



Entangled state

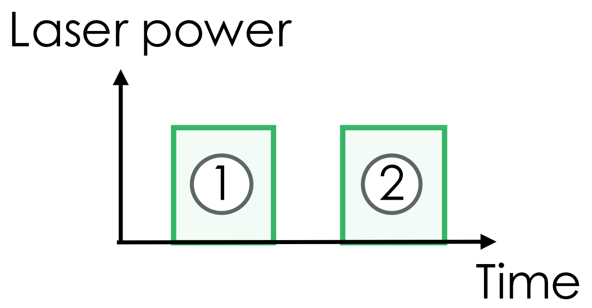
We connect to the $|W\rangle$ state with a strength which is $\sqrt{2}$ higher!

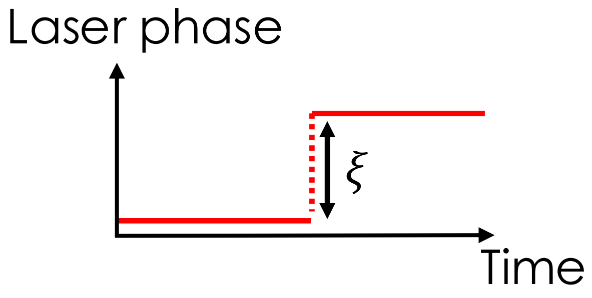
We use this $\sqrt{2}$ increase to do a **controlled-Z** gate

Two-qubit gate through Rydberg interactions

Pasqal

Gate protocol:





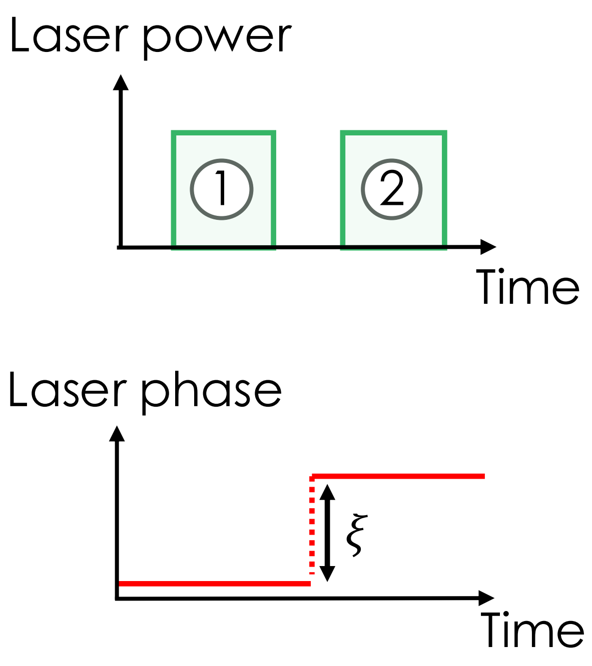
We perform a Controlled-Z (CZ) gate:

input	*Laser pulses effect*	*output*
$\|00\rangle \rightarrow$	Not connected to Rydberg	$\rightarrow \|00\rangle$
$\|01\rangle \rightarrow$	Only a single atom goes in Rydberg	$\rightarrow \|01\rangle$
$\|10\rangle \rightarrow$	Only a single atom goes in Rydberg	$\rightarrow \|10\rangle$
$\|11\rangle \rightarrow$	Both atoms go in Rydberg: blockaded	$\rightarrow -\|11\rangle$

Two-qubit gate through Rydberg interactions

Pasqal

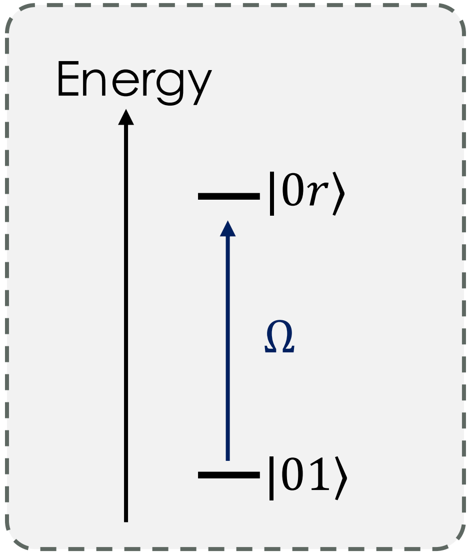
Gate protocol:



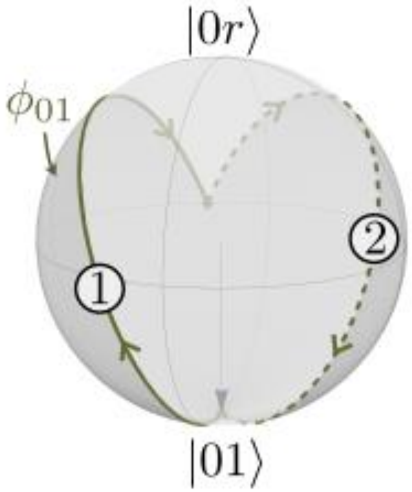
We perform a Controlled-Z (CZ) gate:

input	*Laser pulses effect*	*output*
$\|00\rangle \rightarrow$	Not connected to Rydberg	$\rightarrow \|00\rangle$
$\|01\rangle \rightarrow$	**Only a single atom goes in Rydberg**	$\rightarrow \|01\rangle$
$\|10\rangle \rightarrow$	Only a single atom goes in Rydberg	$\rightarrow \|10\rangle$
$\|11\rangle \rightarrow$	Both atoms go in Rydberg: blockaded	$\rightarrow -\|11\rangle$

Relevant levels:



Dynamics:



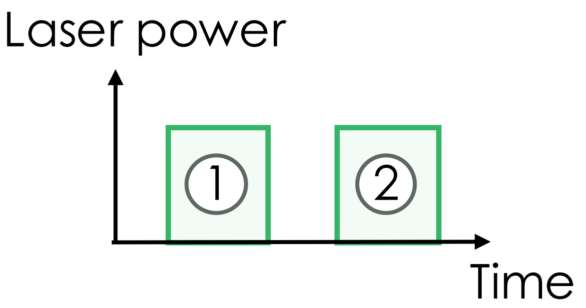
Bloch sphere: very nice tool to represent dynamics in quantum systems

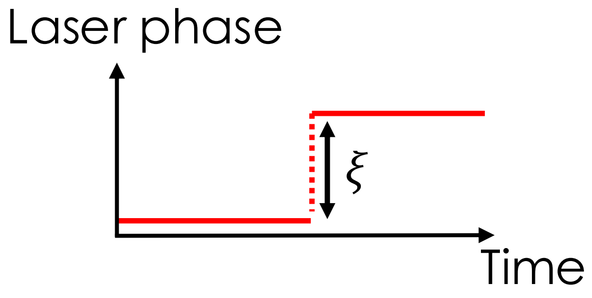
Second pulse brings back to $|01\rangle$

Two-qubit gate through Rydberg interactions

Pasqal

Gate protocol:

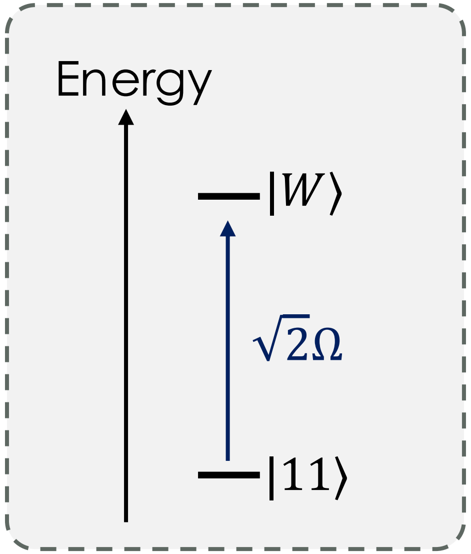




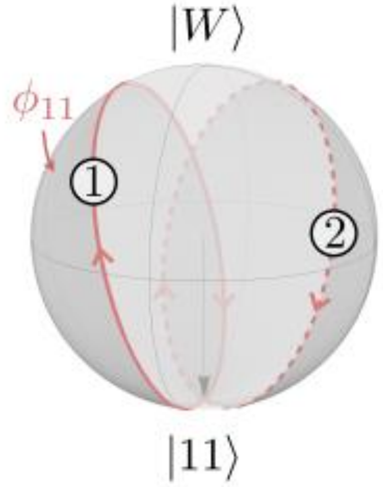
We perform a Controlled-Z (CZ) gate:

input	*Laser pulses effect*	*output*
$\|00\rangle \rightarrow$	Not connected to Rydberg	$\rightarrow \|00\rangle$
$\|01\rangle \rightarrow$	Only a single atom goes in Rydberg	$\rightarrow \|01\rangle$
$\|10\rangle \rightarrow$	Only a single atom goes in Rydberg	$\rightarrow \|10\rangle$
$\|11\rangle \rightarrow$	**Both atoms go in Rydberg: blockaded**	$\rightarrow -\|11\rangle$

Relevant levels:



Dynamics:

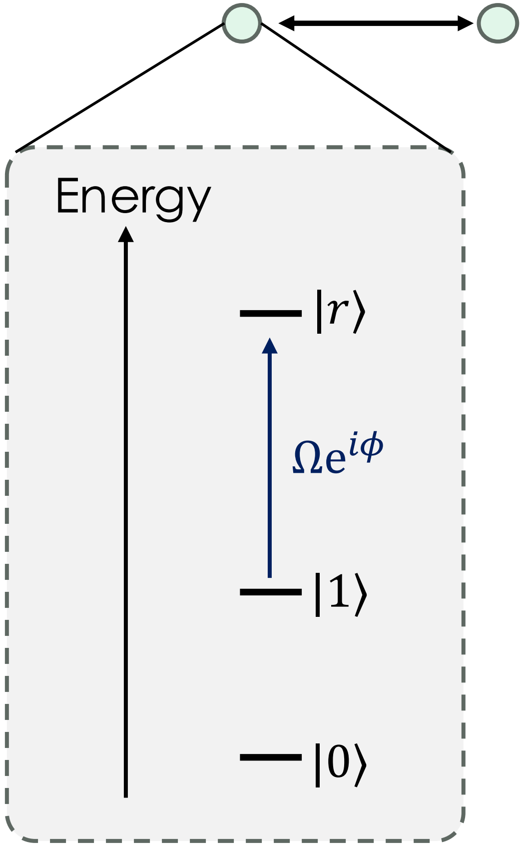


Bloch sphere: very nice tool to represent dynamics in quantum systems

Each pulse ends up in $|11\rangle$ due to the $\sqrt{2}$ increase

Two-qubit gate through Rydberg interactions

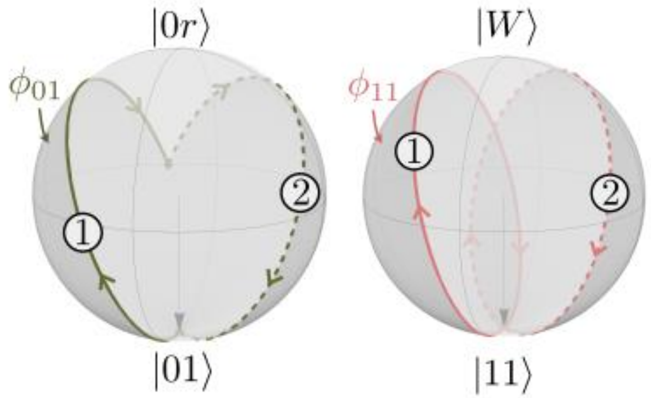
Pasqal



Operate in the **Rydberg blockaded** regime (triggered by atom distance)

Rydberg excitation produces a Bell state: $|W\rangle = (|1r\rangle + |r1\rangle)/\sqrt{2}$

Engineer a controlled-Z gate



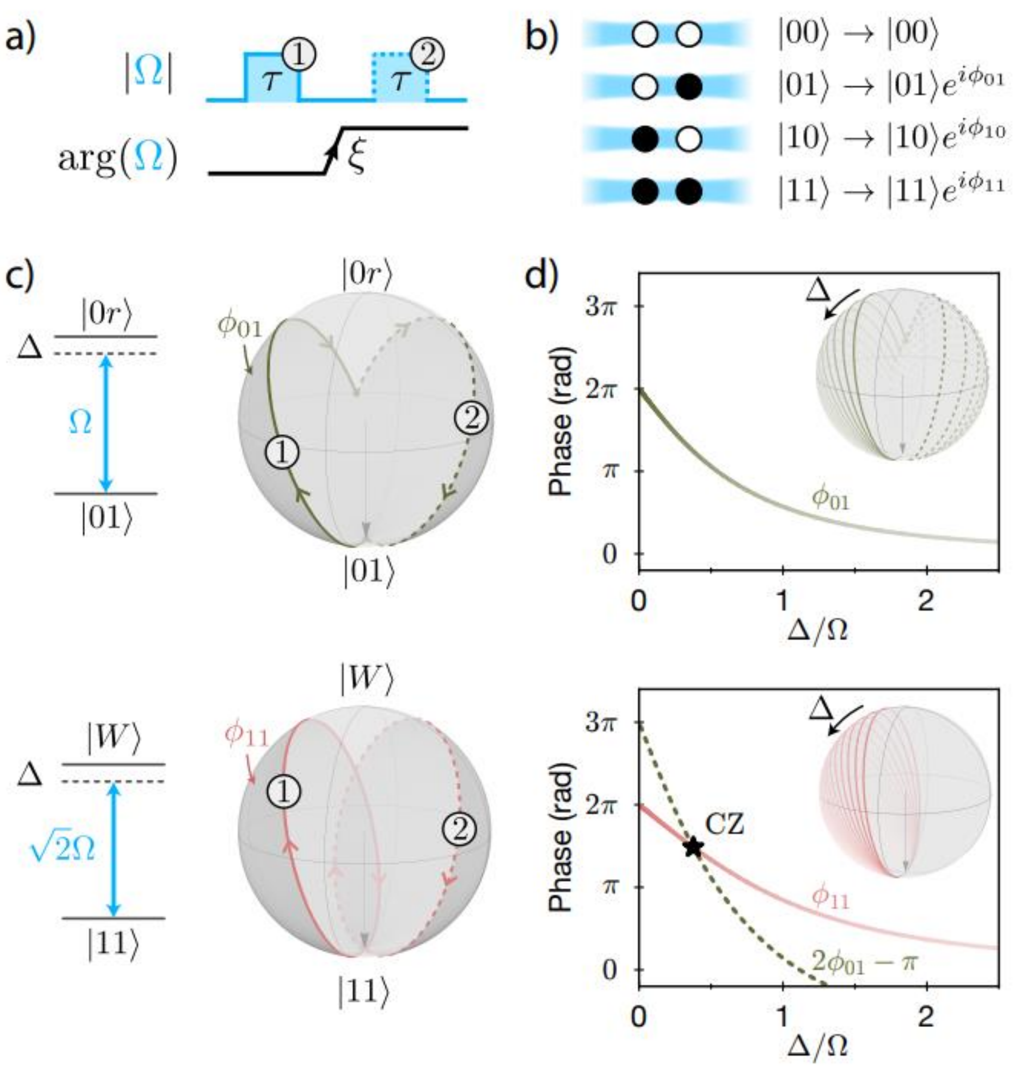
CZ gate

$|00\rangle \rightarrow |00\rangle$
$|01\rangle \rightarrow |01\rangle$
$|10\rangle \rightarrow |10\rangle$
$|11\rangle \rightarrow -|11\rangle$

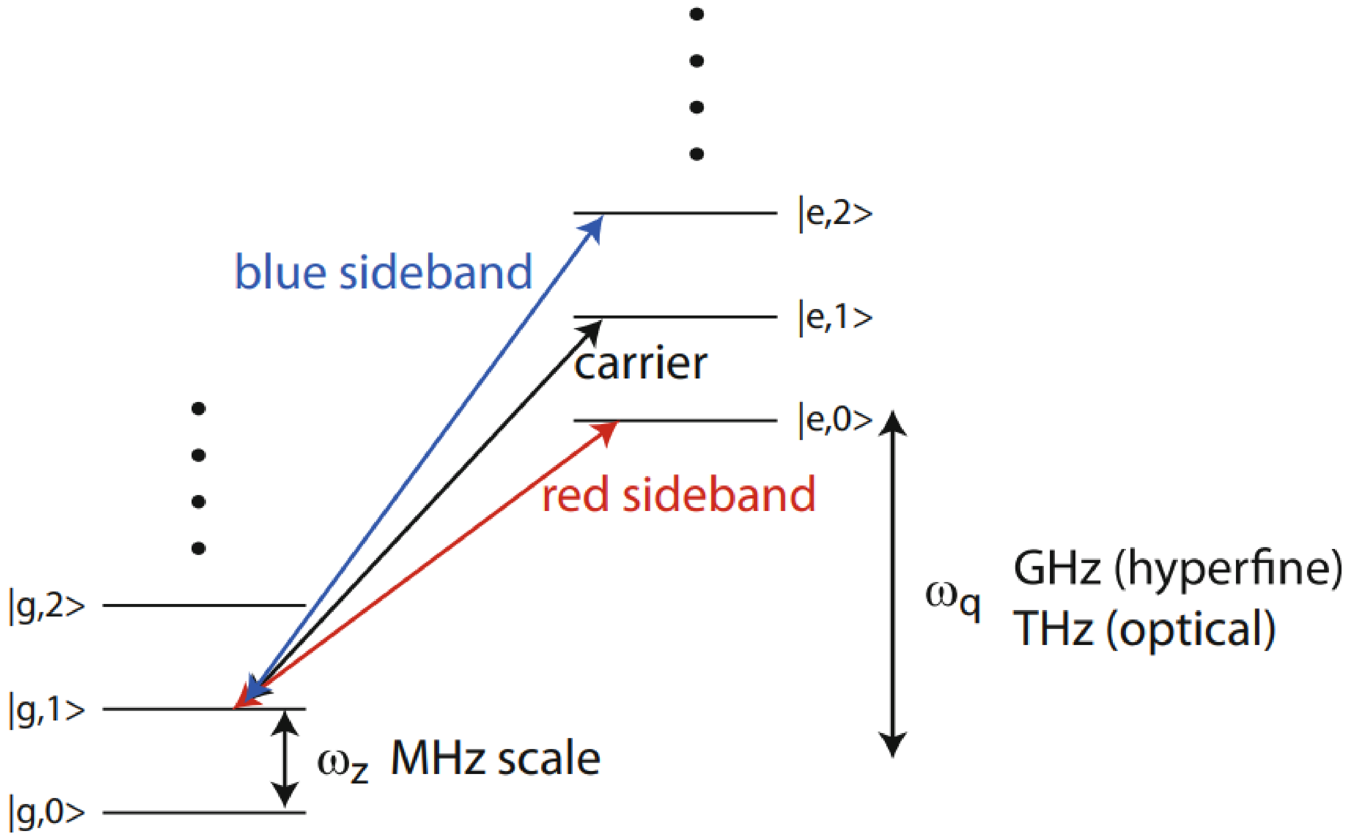
Levine *et al.*, *PRL* **123** (2019)

Gate protocol called Levine-Pichler (LP) gate

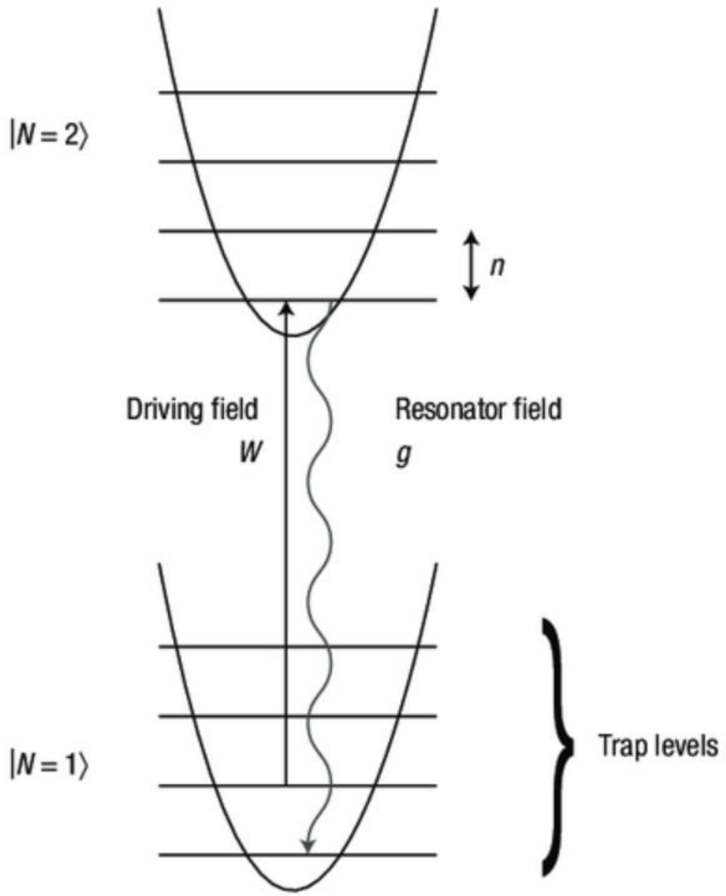
Two-qubit gate through Rydberg interactions



Motional states control



Sideband cooling:



Molmer-Sorensen gate

Pasqal