Global entangling gates on arbitrary ion qubits

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※ Research interest

- Realization of quantum memory and quantum algorithms with two-species of atomic ions

- Quantum simulation with 2D crystal of ions

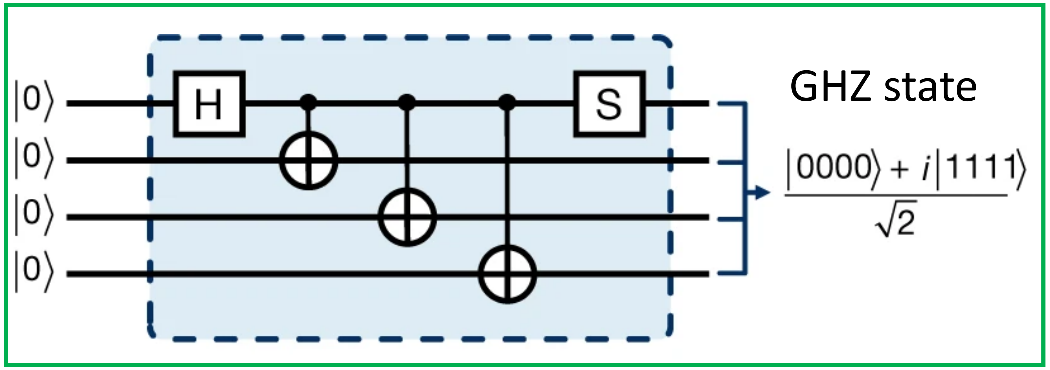
- Quantum computation and simulation with individually controllable ions

Quantum simulation of the quantum rabi model in a trapped ion
PRX 8, 021027 (2018)

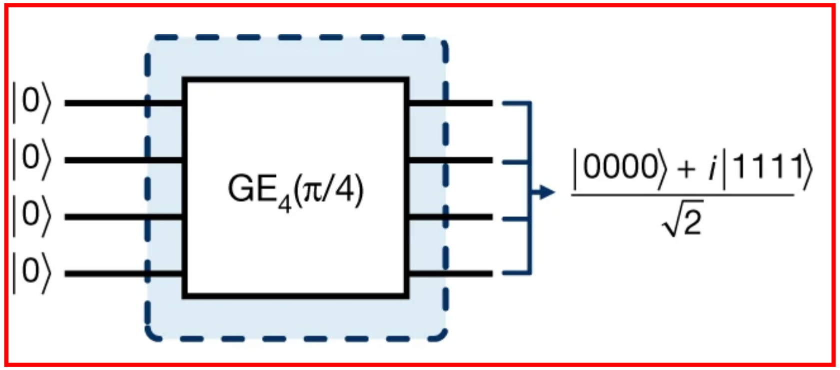
Experimental quantum simulation of fermion-antifermion scattering via boson exchange in a trapped ion
Nature Comm. 9, 195 (2018)

Single-qubit quantum memory exceeding 10-minute coherence time
Nature Photon. 11, 646 (2017)

Universal quantum computation



Decomposition of universal quantum circuit : single- and two-qubit gates
-> Not necessarily efficient



Global entangling gate : a single all to all connected gate
-> polynomial or exponential speedups

- **Global gates using a single motional mode**

# of ions increases -> Difficult to isolate single mode (sacrifice the gate speed)

- **Gates using multiple motional mode**

-> scalable but limited to pairwise gates

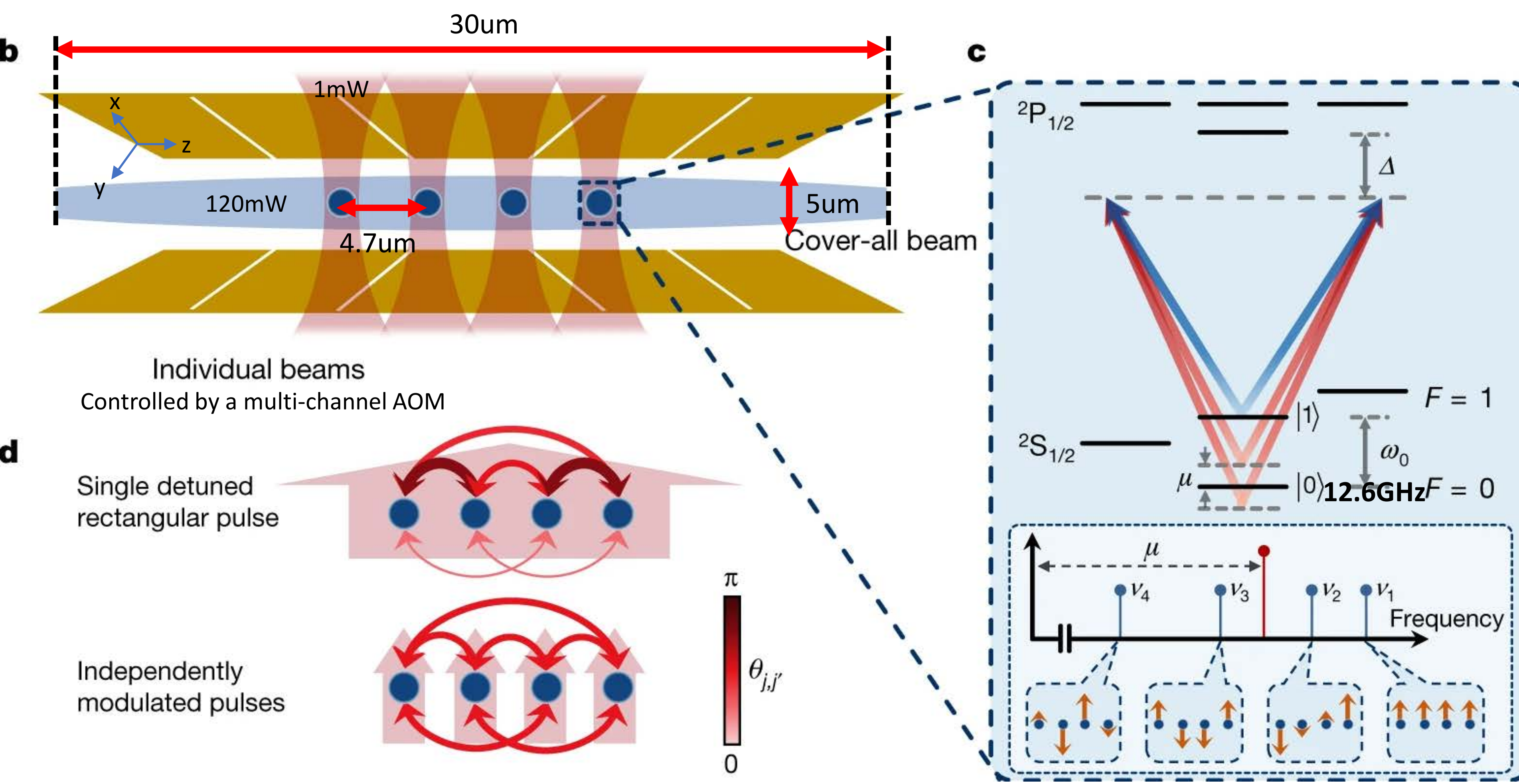
A scalable scheme for global entangling gates

Efficient construction of three- and four-qubit quantum gates by global entangling gates
Svetoslav S. Ivanov, Peter A. Ivanov, and Nikolay V. Vitanov
PRA ***91****, 032311* (2015)

Compiling quantum algorithms for architectures with multi-qubit gates
Esteban A Martinez, Thomas Monz, Daniel Nigg, Philipp Schindler and Rainer Blatt
New J. Phys. ***18***, 063029 (2016)

Use of global interactions in efficient quantum circuit constructions
Dmitri Maslov and Yunseong Nam
New J. Phys. **20**, 033018 (2018)

Experimental scheme



Pulse Optimization

The time evolution operator in trapped ion system

$$U(\tau) = \exp\left(\sum_{j,m} \beta_{j,m}(\tau)\sigma_x^j - i\sum_{j<j'} \theta_{j,j'}\sigma_x^j\sigma_x^{j'}\right)$$

$$\beta_{j,m} = \alpha_{j,m}(\tau)a_m^\dagger - \alpha_{j,m}^*(\tau)a_m$$

$a_m(a_m^\dagger)$ is the annihilation(creation) operator of the mth mode

$\alpha_{j,m}$ is displacement of the mth motional mode of jth ion

Global entangling gate

$$GE_N(\theta) = \exp\left(-i\theta\sum_{j<j'}^{N} \sigma_x^j\sigma_x^{j'}\right)$$

$$\theta_{j,j'}(\tau) = -\sum_m \int_0^\tau dt_2 \int_0^{t_2} dt_1 \frac{\eta_{j,m}\eta_{j',m}\Omega_j(t_2)\Omega_{j'}(t_1)}{2} sin\left[(\nu_m - \mu)(t_2 - t_1) - \left(\varphi_j(t_2) - \varphi_{j'}(t_1)\right)\right]$$

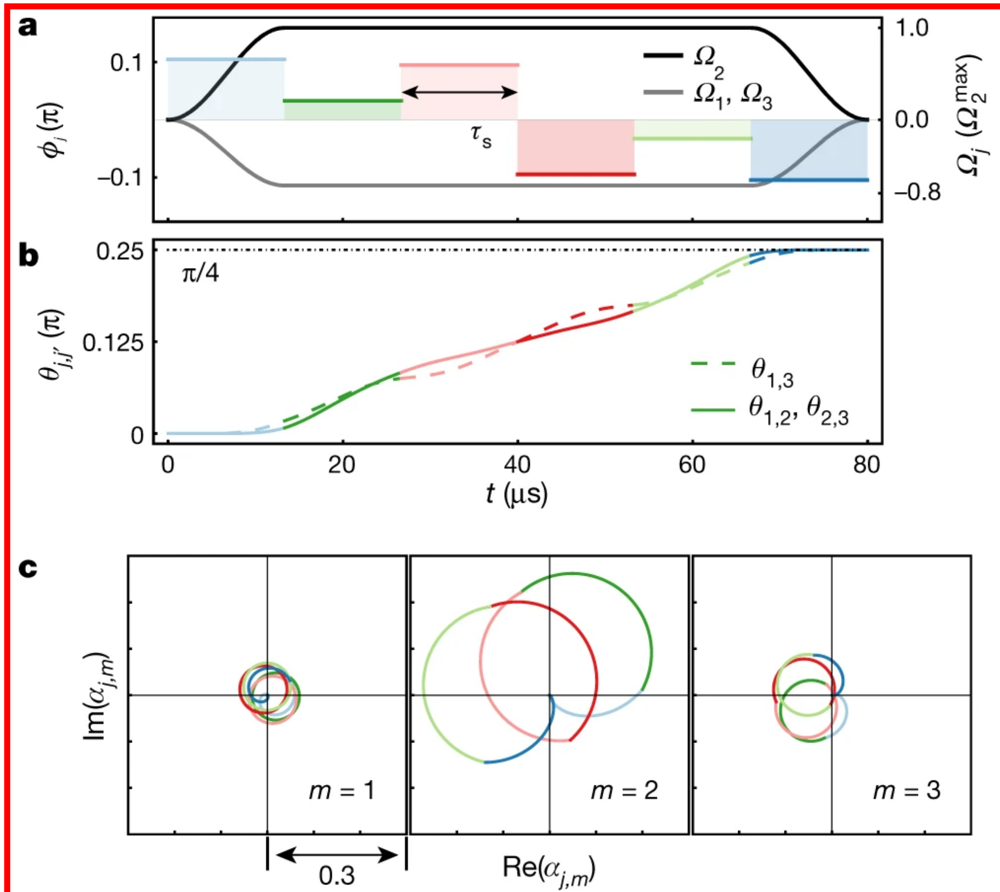
$$\alpha_{j,m}(\tau) = -i\eta_{j,m}\int_0^\tau \frac{\Omega_j(t)e^{-i\varphi_j(t)}}{2} e^{i(\nu_m-\mu)t}dt$$

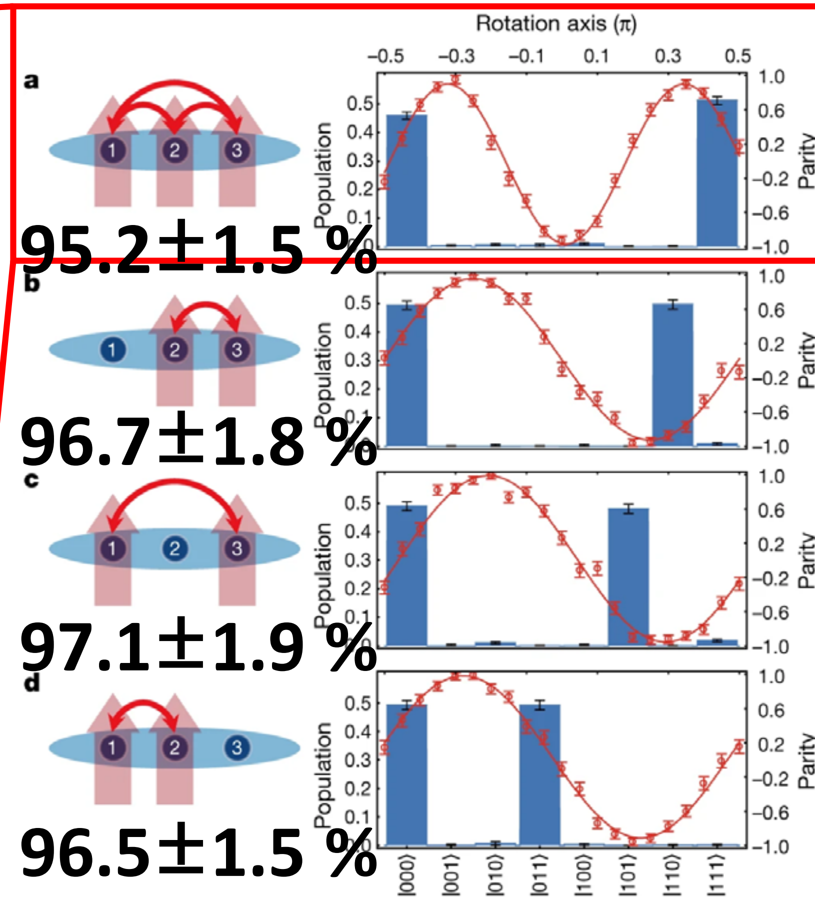
Constraint : $\alpha_{j,m}$ = 0, $\theta_{j,j'}$ = Θ(in GHZ case, $\frac{\pi}{4}$)

Global three-qubit entangling gate

Motional mode frequency
$\{\nu_1, \nu_2, \nu_3\} = 2\pi \times \{2.184, 2.127, 2.044\}\text{MHz}$

detuning
$\mu = 2\pi \times 2.094\text{MHz}$





95.2±1.5 %

96.7±1.8 %

97.1±1.9 %

96.5±1.5 %

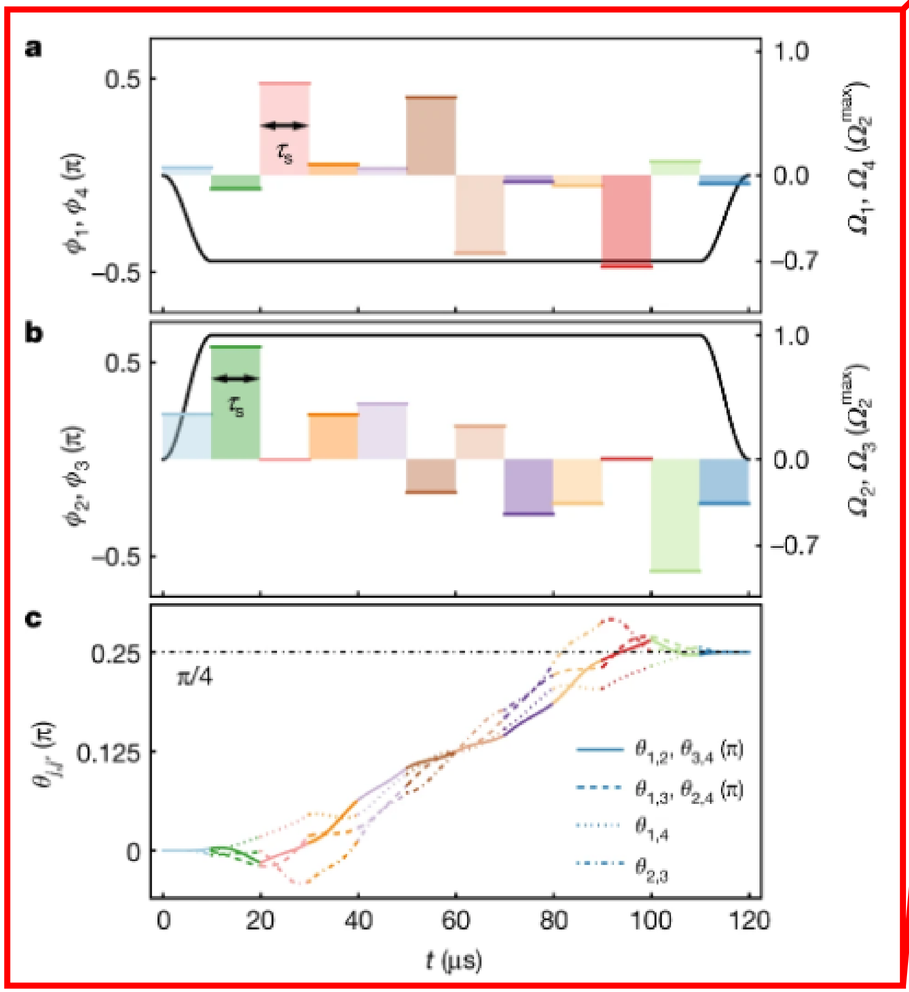
Extended Data Table 1 | Pulse scheme for the global three-qubit entangling gate

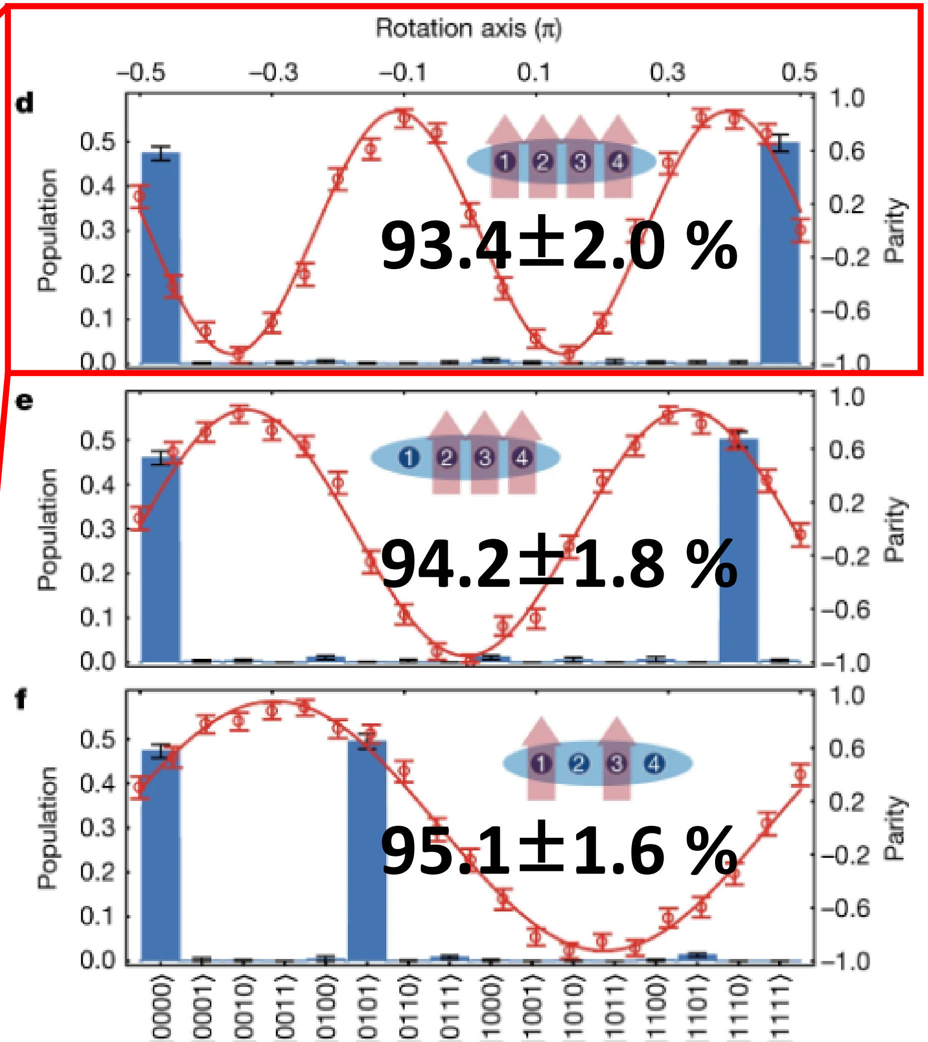
Qubit j		1	2	3
Ω_j^{max} (MHz)		$-2\pi \times 0.181$	$2\pi \times 0.253$	$-2\pi \times 0.181$
$\phi_{j,k}$ (π)	1	0.104	0.104	0.104
	2	0.033	0.033	0.033
	3	0.095	0.095	0.095
	4	-0.095	-0.095	-0.095
	5	-0.033	-0.033	-0.033
	6	-0.104	-0.104	-0.104

Here, Ω_j^{max} refers to the maximal amplitude of the Rabi frequency on the jth qubit during pulse shaping and $\phi_{j,k}$ refers to the value of the modulated phase on the jth qubit in the kth segment.

Global four-qubit entangling gate

$\{\nu_1, \nu_2, \nu_3, \nu_4\} = 2\pi \times \{2.186, 2.147, 2.091, 2.020\}\text{MHz}$ $\mu = 2\pi \times 2.104\text{MHz}$





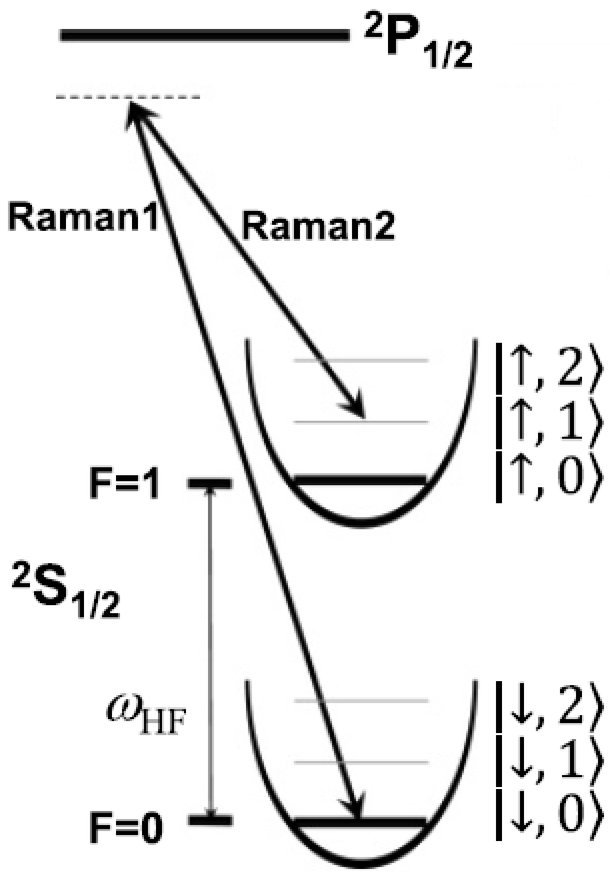
Extended Data Table 2 | Pulse scheme for the global four-qubit entangling gate

Qubit j		1	2	3	4
Ω_j^{max} (MHz)		$-2\pi \times 0.117$	$2\pi \times 0.168$	$2\pi \times 0.168$	$-2\pi \times 0.117$
$\phi_{j,k}$ (π)	1	0.041	0.231	0.231	0.041
	2	-0.070	0.579	0.579	-0.070
	3	0.472	-0.001	-0.001	0.472
	4	0.054	0.230	0.230	0.054
	5	0.035	0.285	0.285	0.035
	6	0.402	-0.170	-0.170	0.402
	7	-0.402	0.170	0.170	-0.402
	8	-0.035	-0.285	-0.285	-0.035
	9	-0.054	-0.230	-0.230	-0.054
	10	-0.472	0.001	0.001	-0.472
	11	0.070	-0.579	-0.579	0.070
	12	-0.041	-0.231	-0.231	-0.041

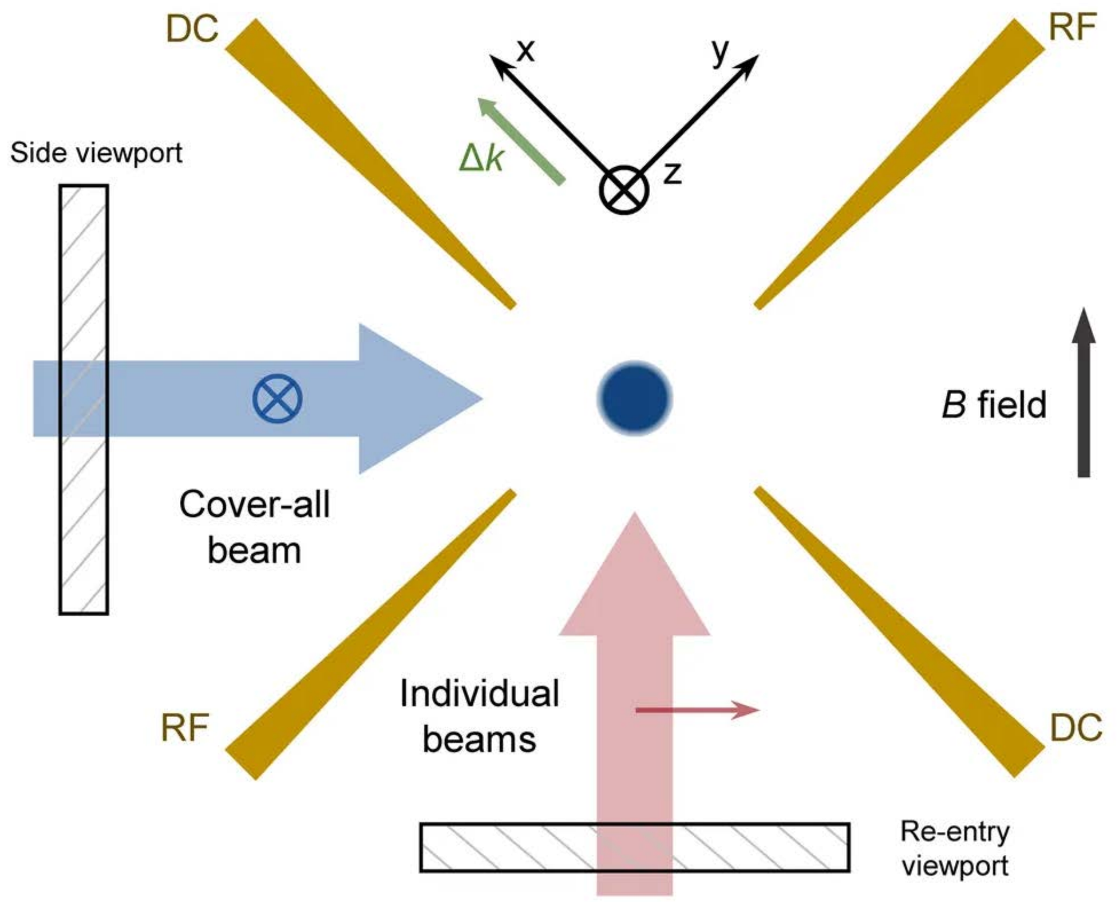
The definitions of Ω_j^{max} and $\phi_{j,k}$ are as in Extended Data Table 1.

Conclusion

- Implementation of the universal quantum computation by global entangling gate
- Scalable scheme for global entangling gates by coupling to multiple motional modes
- Pulse optimization can be done by solving the minimization problem
- Pulse optimization with a large number of qubits should be assisted by a classical machine learning technique
- The solution of the global N-qubit entangling gate can be applied on any subset of qubits by simply setting $\Omega_j = 0$



²P1/2
Raman1
Raman2
|↑, 2⟩
|↑, 1⟩
|↑, 0⟩
F=1
²S1/2
ωHF
F=0
|↓, 2⟩
|↓, 1⟩
|↓, 0⟩


DC
RF
x
y
Δk
z
Side viewport
B field
Cover-all beam
Individual beams
RF
DC
Re-entry viewport