IMPERIAL

Quantum Compilation

With Neutral Atoms

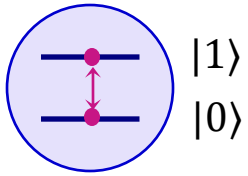
Chen Huang

13/04/2025

Quantum bits (Qubits)

Basic carriers of quantum information

A theoretician's qubit:



$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle \qquad |\alpha|^2 + |\beta|^2 = 1$$

Naturally occurring qubits: electrons, protons (spin-1/2 systems), photons (two polarization states)

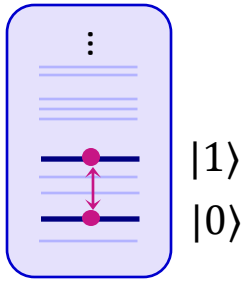
But: unbound electron ⟷ wave packet in position or momentum space

photon wave packet ⟷ energy dispersion

Engineered quantum system: atoms, molecules, solid state systems

But: many energy levels

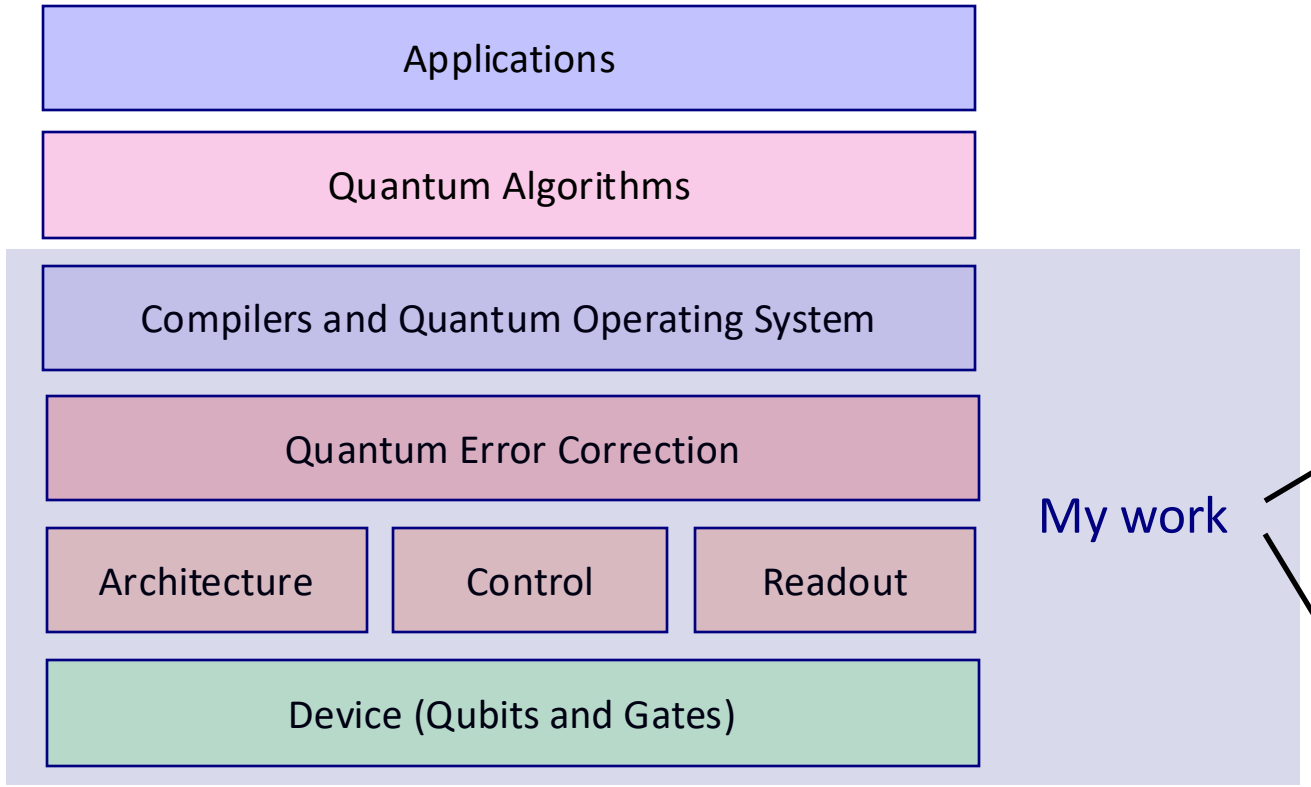
An experimentalist's qubit:



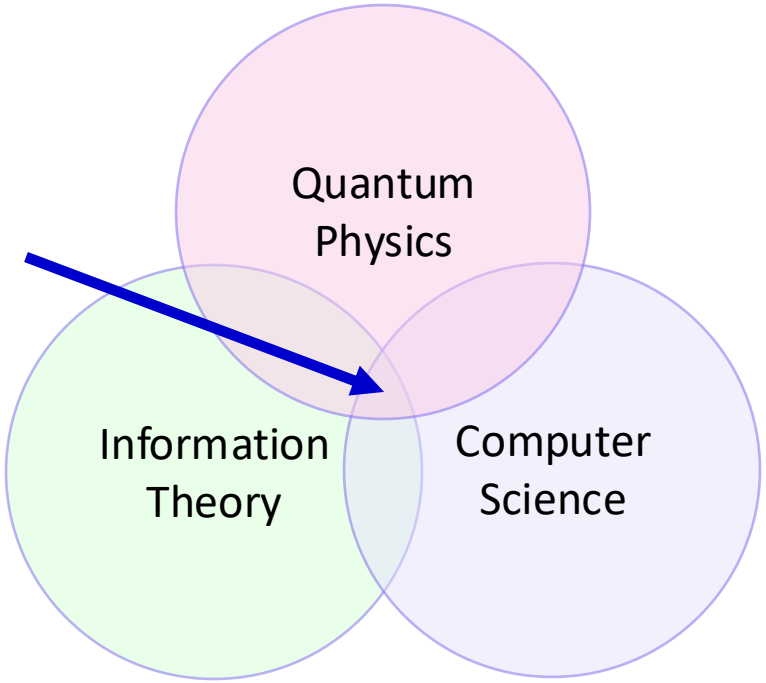
Quantum computing stack
How to build a quantum computer?

Logical layer

Physical layer



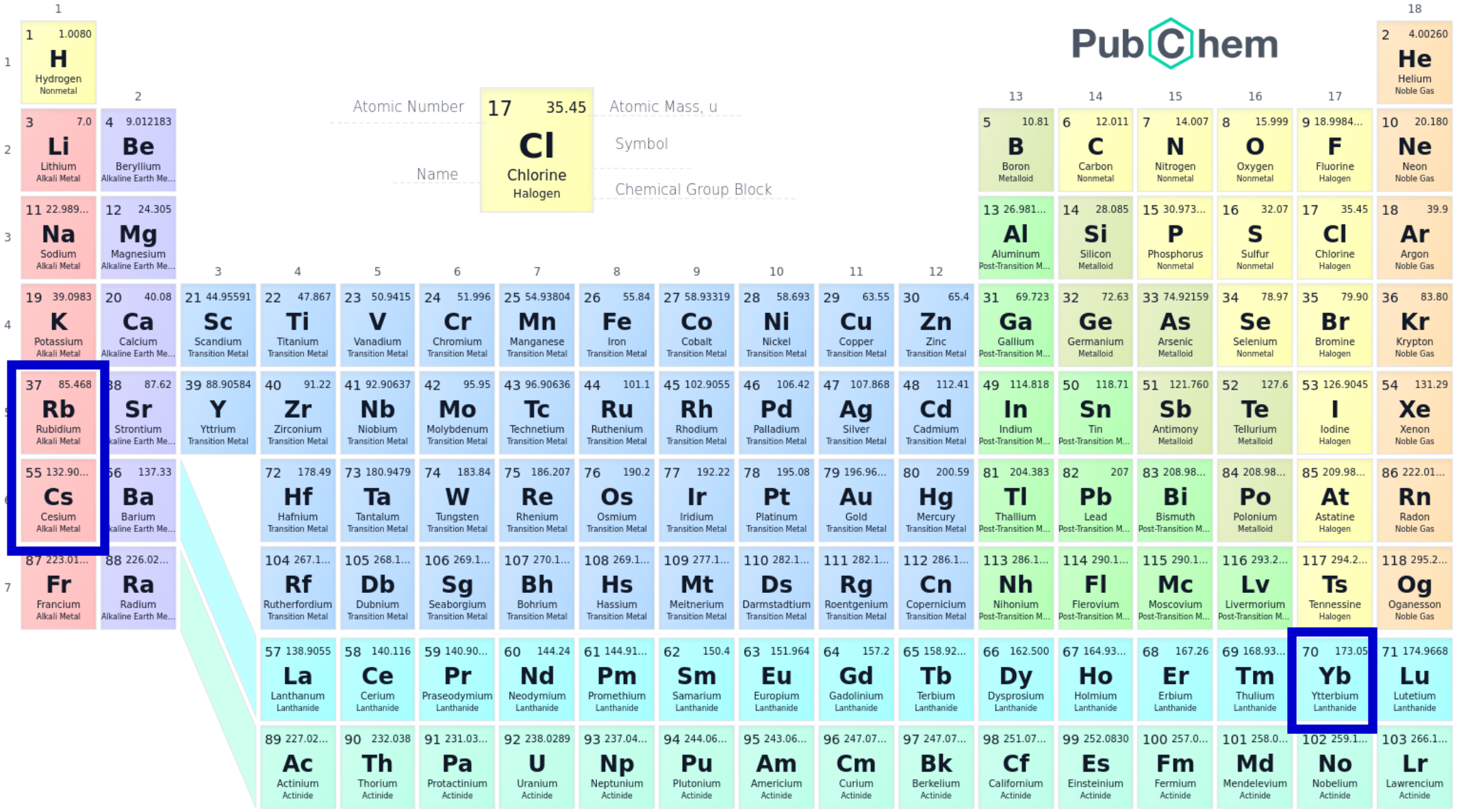
Quantum Computing



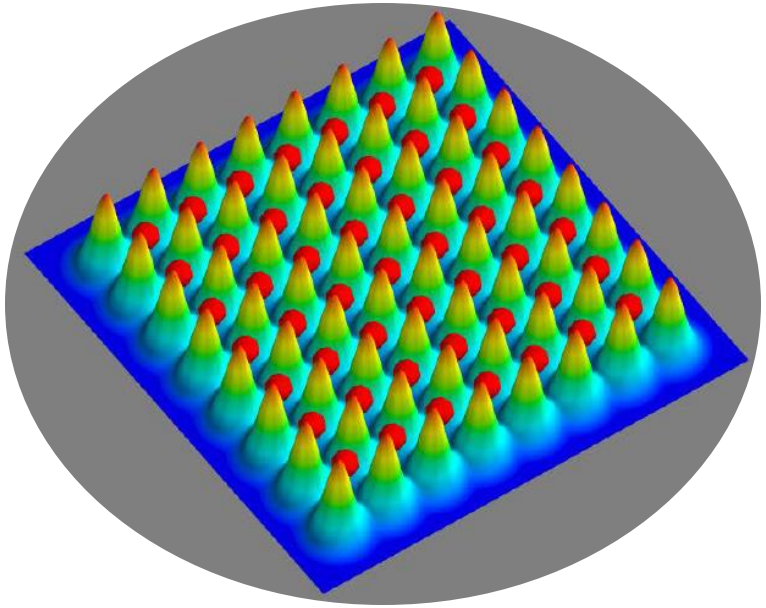
My work

QC stack optimization
- Quantum circuit compilation
- Boise model

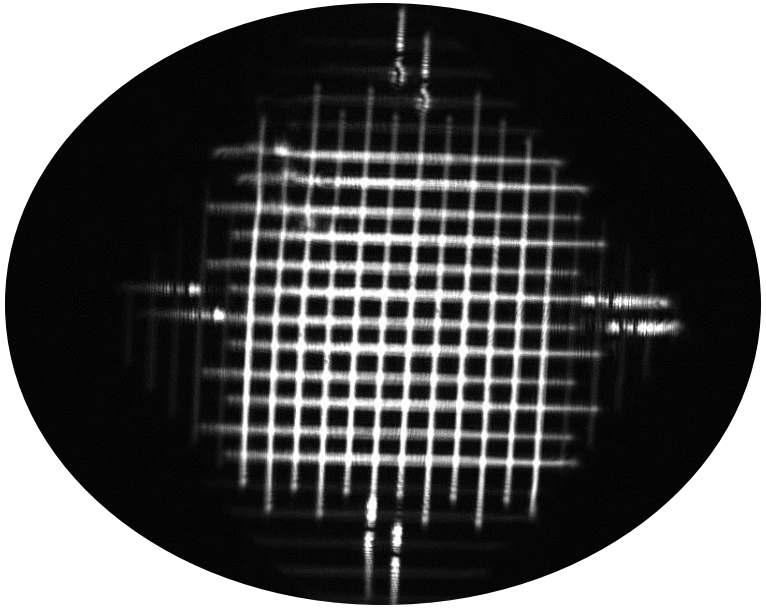
Hardware
- Neutral atoms
- Trapped ions
- Semiconductor charge qubits


PubChem
Atomic Number
17
35.45
Atomic Mass, u
Cl
Chlorine
Halogen
Name
Symbol
Chemical Group Block
1 1.0080 H Hydrogen Nonmetal
2 4.00260 He Helium Noble Gas
3 7.0 Li Lithium Alkali Metal
4 9.012183 Be Beryllium Alkaline Earth Me...
5 10.81 B Boron Metalloid
6 12.011 C Carbon Nonmetal
7 14.007 N Nitrogen Nonmetal
8 15.999 O Oxygen Nonmetal
9 18.9984... F Fluorine Halogen
10 20.180 Ne Neon Noble Gas
11 22.989... Na Sodium Alkali Metal
12 24.305 Mg Magnesium Alkaline Earth Me...
13 26.981... Al Aluminum Post-Transition M...
14 28.085 Si Silicon Metalloid
15 30.973... P Phosphorus Nonmetal
16 32.07 S Sulfur Nonmetal
17 35.45 Cl Chlorine Halogen
18 39.9 Ar Argon Noble Gas
19 39.0983 K Potassium Alkali Metal
20 40.08 Ca Calcium Alkaline Earth Me...
21 44.95591 Sc Scandium Transition Metal
22 47.867 Ti Titanium Transition Metal
23 50.9415 V Vanadium Transition Metal
24 51.996 Cr Chromium Transition Metal
25 54.93804 Mn Manganese Transition Metal
26 55.84 Fe Iron Transition Metal
27 58.93319 Co Cobalt Transition Metal
28 58.693 Ni Nickel Transition Metal
29 63.55 Cu Copper Transition Metal
30 65.4 Zn Zinc Transition Metal
31 69.723 Ga Gallium Post-Transition M...
32 72.63 Ge Germanium Metalloid
33 74.92159 As Arsenic Metalloid
34 78.97 Se Selenium Nonmetal
35 79.90 Br Bromine Halogen
36 83.80 Kr Krypton Noble Gas
37 85.468 Rb Rubidium Alkali Metal
38 87.62 Sr Strontium Alkaline Earth Me...
39 88.90584 Y Yttrium Transition Metal
40 91.22 Zr Zirconium Transition Metal
41 92.90637 Nb Niobium Transition Metal
42 95.95 Mo Molybdenum Transition Metal
43 96.90636 Tc Technetium Transition Metal
44 101.1 Ru Ruthenium Transition Metal
45 102.9055 Rh Rhodium Transition Metal
46 106.42 Pd Palladium Transition Metal
47 107.868 Ag Silver Transition Metal
48 112.41 Cd Cadmium Transition Metal
49 114.818 In Indium Post-Transition M...
50 118.71 Sn Tin Post-Transition M...
51 121.760 Sb Antimony Metalloid
52 127.6 Te Tellurium Metalloid
53 126.9045 I Iodine Halogen
54 131.29 Xe Xenon Noble Gas
55 132.90... Cs Cesium Alkali Metal
56 137.33 Ba Barium Alkaline Earth Me...
72 178.49 Hf Hafnium Transition Metal
73 180.9479 Ta Tantalum Transition Metal
74 183.84 W Tungsten Transition Metal
75 186.207 Re Rhenium Transition Metal
76 190.2 Os Osmium Transition Metal
77 192.22 Ir Iridium Transition Metal
78 195.08 Pt Platinum Transition Metal
79 196.96... Au Gold Transition Metal
80 200.59 Hg Mercury Transition Metal
81 204.383 Tl Thallium Post-Transition M...
82 207 Pb Lead Post-Transition M...
83 208.98... Bi Bismuth Post-Transition M...
84 208.98... Po Polonium Metalloid
85 209.98... At Astatine Halogen
86 222.01... Rn Radon Noble Gas
87 223.01... Fr Francium Alkali Metal
88 226.02... Ra Radium Alkaline Earth Me...
104 267.1... Rf Rutherfordium Transition Metal
105 268.1... Db Dubnium Transition Metal
106 269.1... Sg Seaborgium Transition Metal
107 270.1... Bh Bohrium Transition Metal
108 269.1... Hs Hassium Transition Metal
109 277.1... Mt Meitnerium Transition Metal
110 282.1... Ds Darmstadtium Transition Metal
111 282.1... Rg Roentgenium Transition Metal
112 286.1... Cn Copernicium Transition Metal
113 286.1... Nh Nihonium Post-Transition M...
114 290.1... Fl Flerovium Post-Transition M...
115 290.1... Mc Moscovium Post-Transition M...
116 293.2... Lv Livermorium Post-Transition M...
117 294.2... Ts Tennessine Halogen
118 295.2... Og Oganesson Noble Gas
57 138.9055 La Lanthanum Lanthanide
58 140.116 Ce Cerium Lanthanide
59 140.90... Pr Praseodymium Lanthanide
60 144.24 Nd Neodymium Lanthanide
61 144.91... Pm Promethium Lanthanide
62 150.4 Sm Samarium Lanthanide
63 151.964 Eu Europium Lanthanide
64 157.2 Gd Gadolinium Lanthanide
65 158.92... Tb Terbium Lanthanide
66 162.500 Dy Dysprosium Lanthanide
67 164.93... Ho Holmium Lanthanide
68 167.26 Er Erbium Lanthanide
69 168.93... Tm Thulium Lanthanide
70 173.05 Yb Ytterbium Lanthanide
71 174.9668 Lu Lutetium Lanthanide
89 227.02... Ac Actinium Actinide
90 232.038 Th Thorium Actinide
91 231.03... Pa Protactinium Actinide
92 238.0289 U Uranium Actinide
93 237.04... Np Neptunium Actinide
94 244.06... Pu Plutonium Actinide
95 243.06... Am Americium Actinide
96 247.07... Cm Curium Actinide
97 247.07... Bk Berkelium Actinide
98 251.07... Cf Californium Actinide
99 252.0830 Es Einsteinium Actinide
100 257.0... Fm Fermium Actinide
101 258.0... Md Mendelevium Actinide
102 259.1... No Nobelium Actinide
103 266.1... Lr Lawrencium Actinide

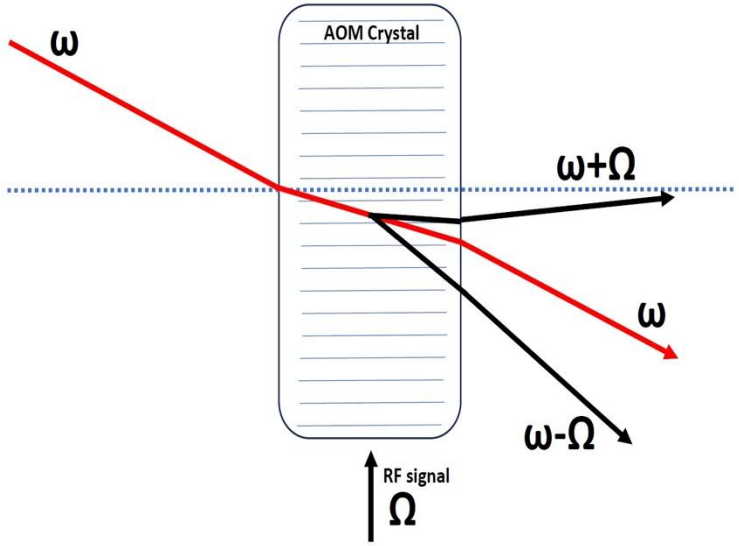
Quantum computing with neutral atoms
Platform



SLM
Spatial Light Modulator

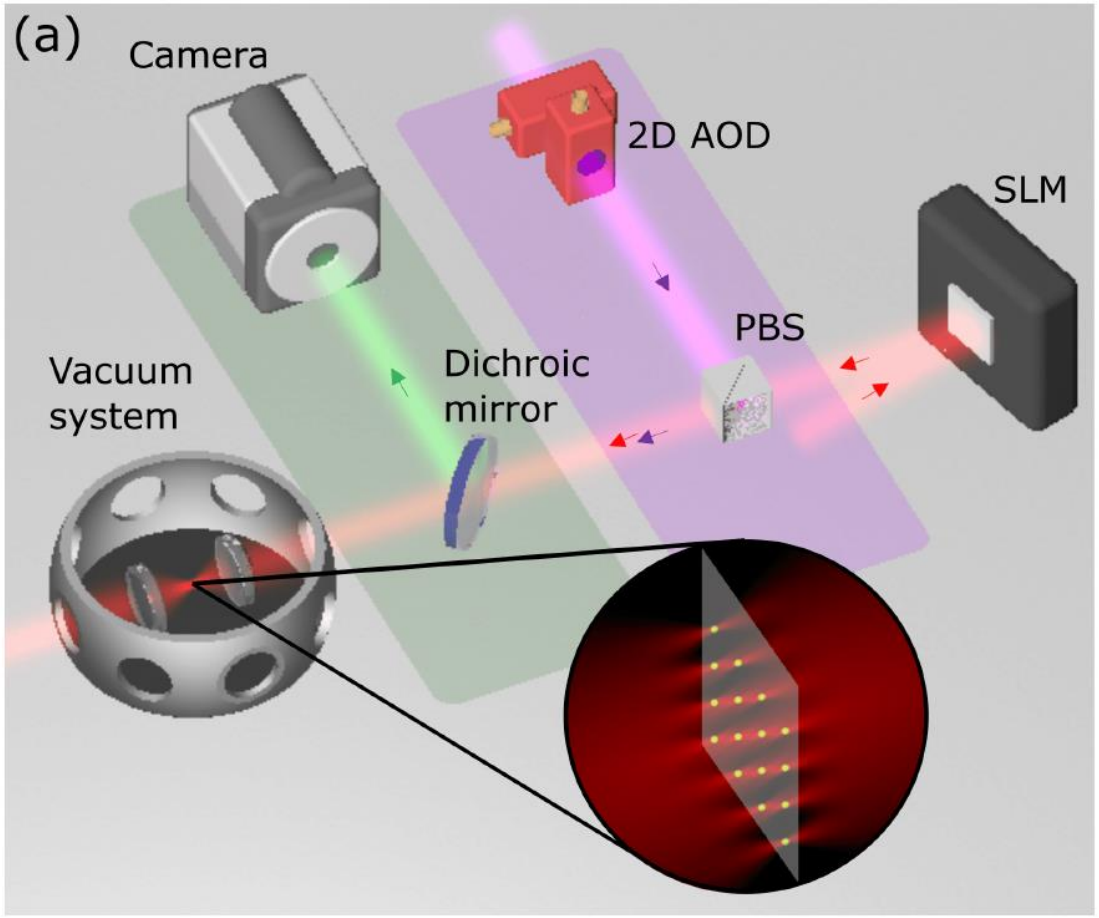


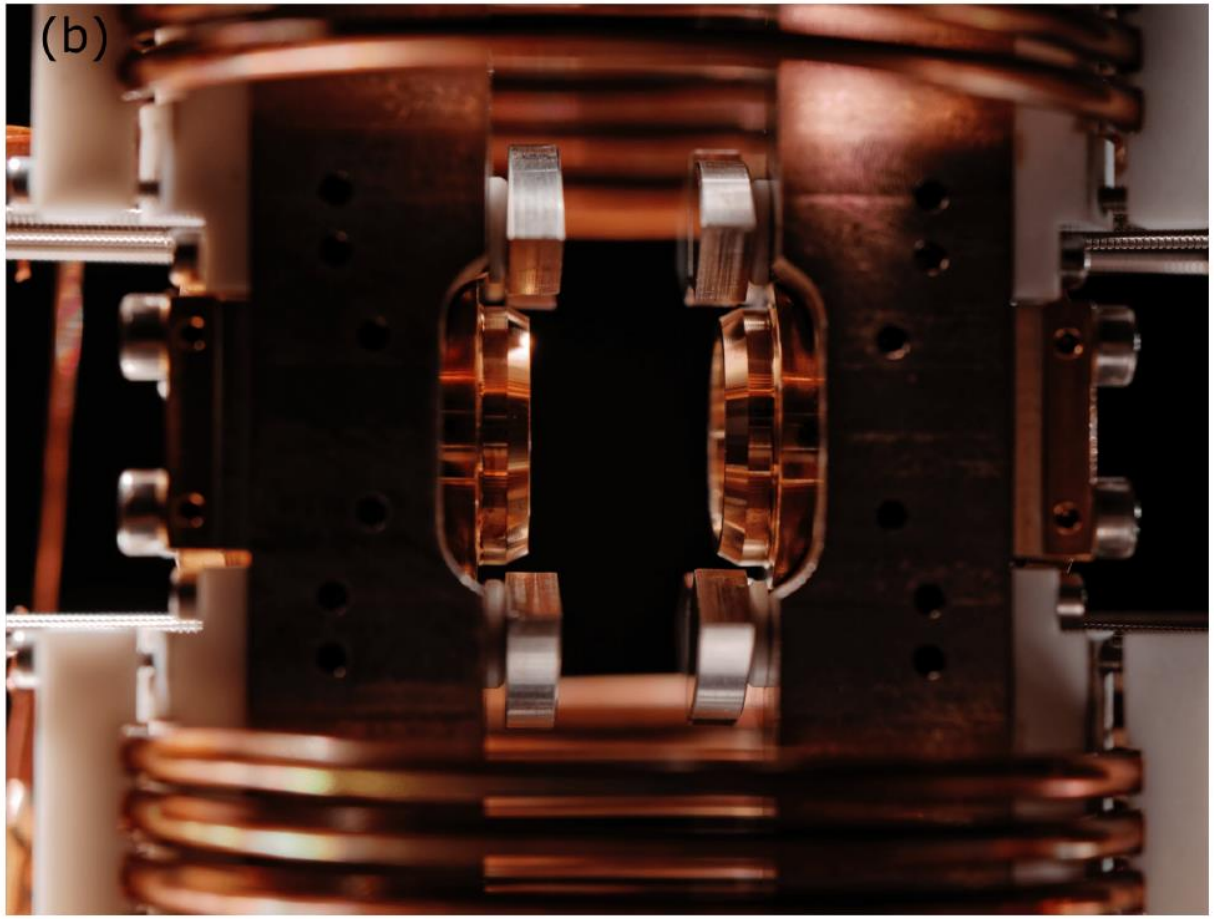
AOD
Acousto-Optic Deflector



AOM
Acousto-Optic Modulator

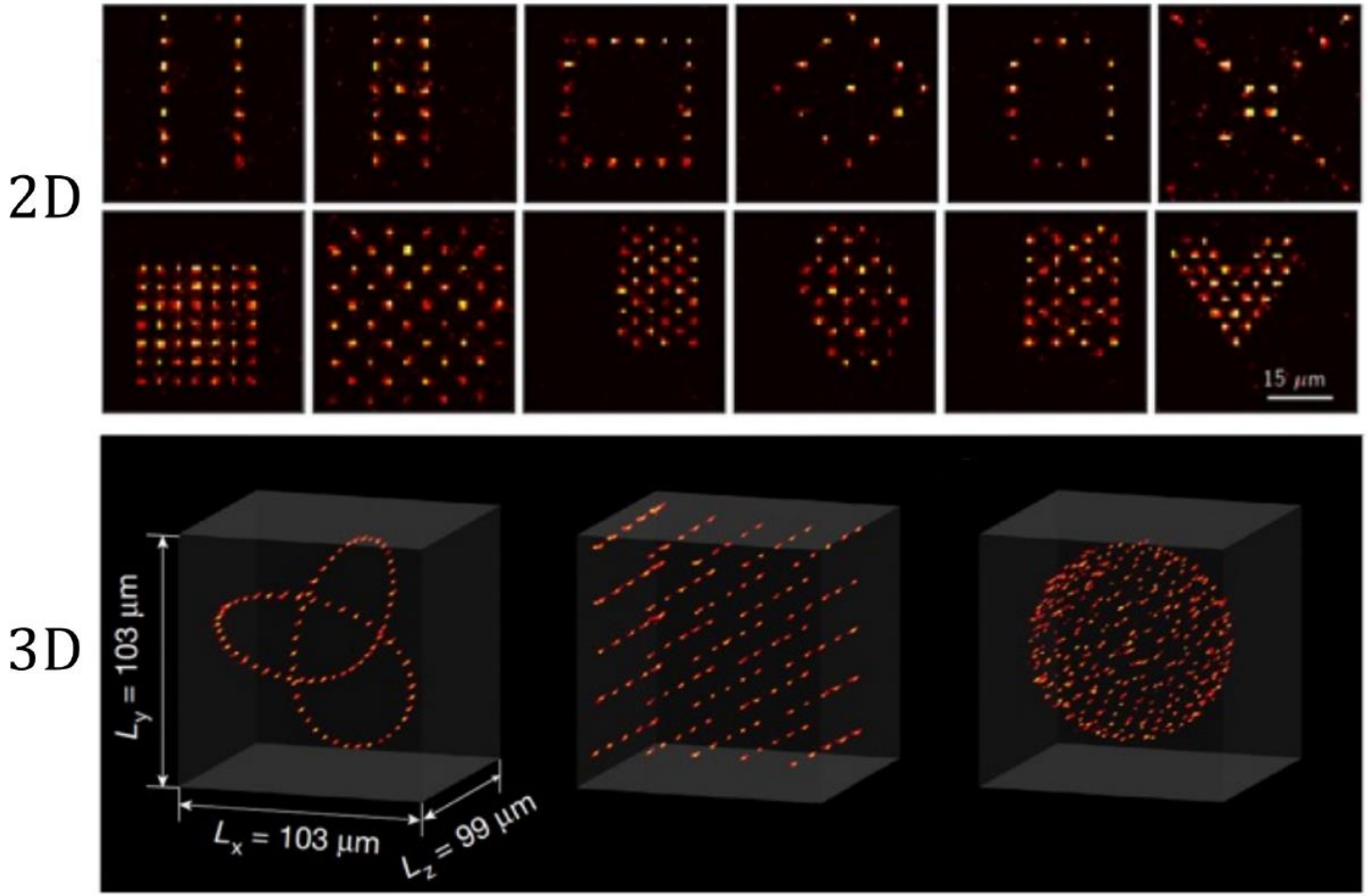
Quantum computing with neutral atoms
Platform





Henriet, Loïc, et al. "Quantum computing with neutral atoms." *Quantum* 4 (2020): 327.

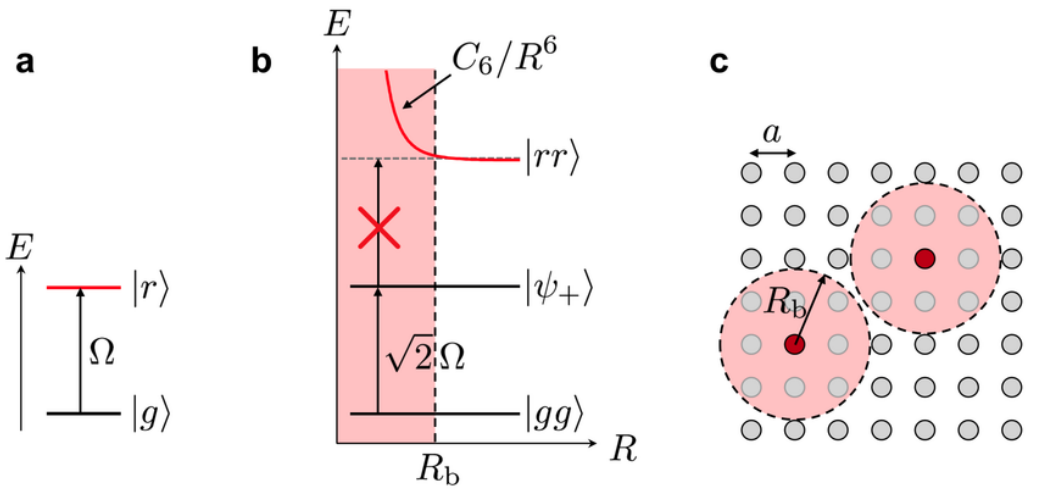
Quantum computing with neutral atoms
Platform

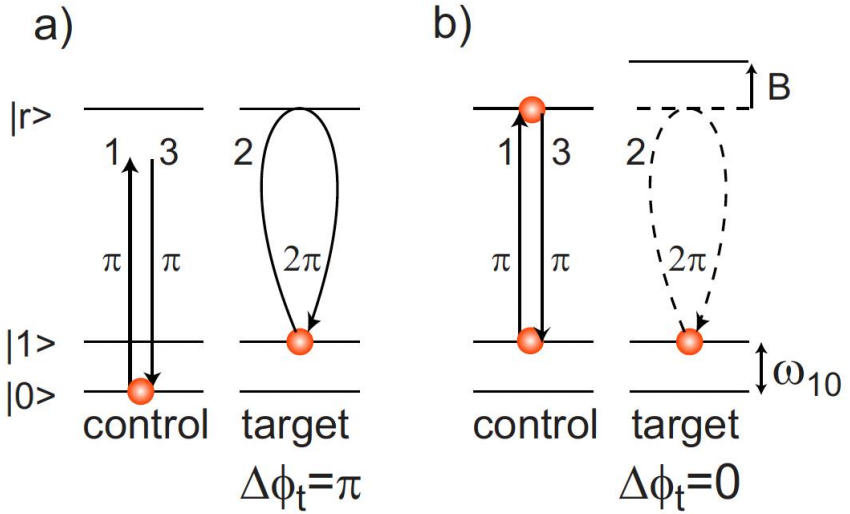


Barredo, Daniel, et al. "Synthetic three-dimensional atomic structures assembled atom by atom." *Nature* 561.7721 (2018): 79-82.

Quantum computing with neutral atoms
Coulomb blockade

van der Waals interaction





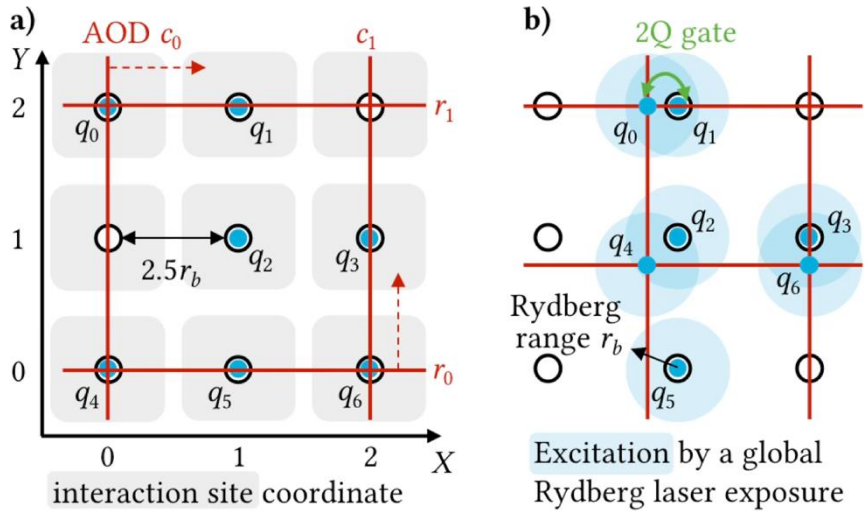
$$H = \sum_i \left(-\frac{\hbar\Delta}{2}\sigma_z^{(i)} + \frac{\hbar\Omega}{2}(\sigma_x^{(i)}) \right) + \sum_{i<j} \frac{C_6}{r_{ij}^6} |r_i r_j\rangle\langle r_i r_j|$$

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

Quantum compilation

Fidelity analysis and scheduling

Platform



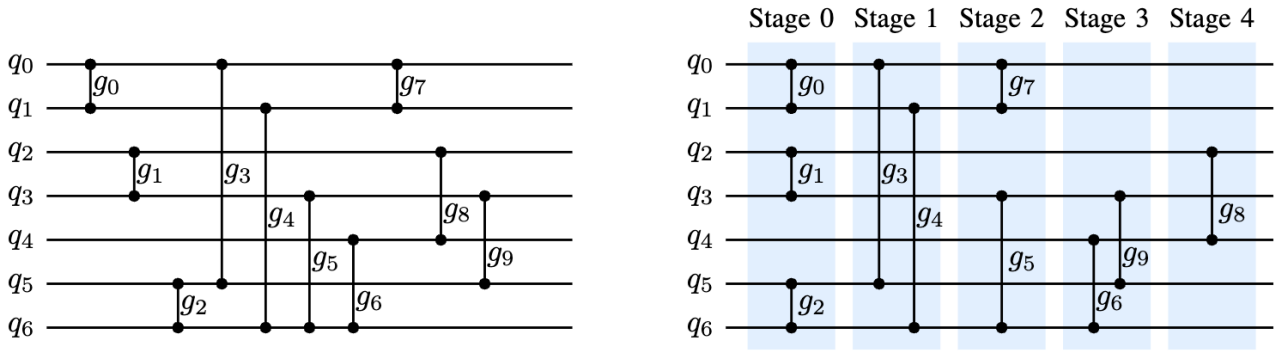
Fidelity

$$f = (f_1)^{g_1} \cdot (f_2)^{g_2} \cdot (f_{\text{crosstalk}})^{N_{\text{crosstalk}}} \cdot (f_{\text{trans}})^{N_{\text{trans}}} \times \prod_{q \in Q} \left(1 - \frac{t_q}{T_2}\right).$$

ZAP: Zoned Architecture and Parallelizable Compiler for Field Programmable Atom Array

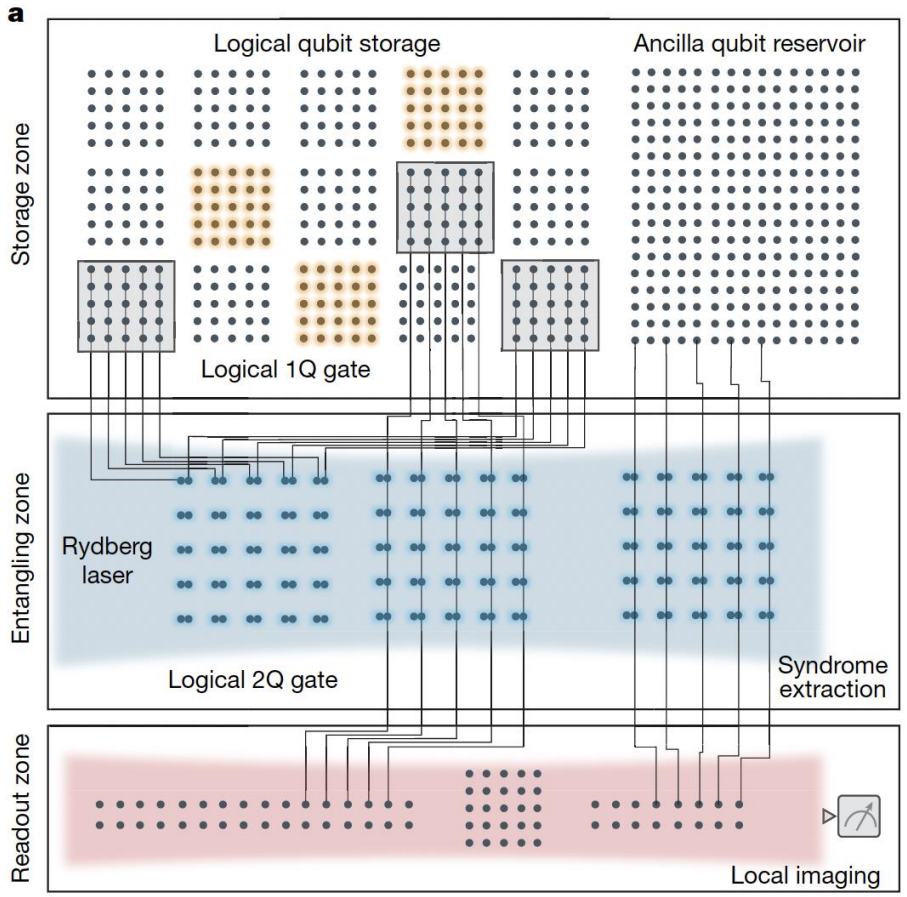
Chen Huang[†,1,5], Xi Zhao[†,1,6], Hongze Xu[†,1], Weifeng Zhuang[1],
Meng-Jun Hu[1,a], Dong E. Liu[1,2,3,4,b], Jingbo Wang[1,c]
[1]Beijing Academy of Quantum Information Sciences, Beijing 100193, China
[2]State Key Laboratory of Low Dimensional Quantum Physics,
Department of Physics, Tsinghua University, Beijing 100084, China
[3]Frontier Science Center for Quantum Information, Beijing 100184, China
[4]Hefei National Laboratory, Hefei 230088, China
[5]Blackett Laboratory, Imperial College London, London SW7 2AZ, United Kingdom
[6]CAS Key Laboratory of Quantum Information, University of Science and Technology of China, Hefei 230026, China
[†]These authors contributed equally to this work.
Email: [a]humj@baqis.ac.cn, [b]dongeliu@mail.tsinghua.edu.cn, [c]wangjb@baqis.ac.cn

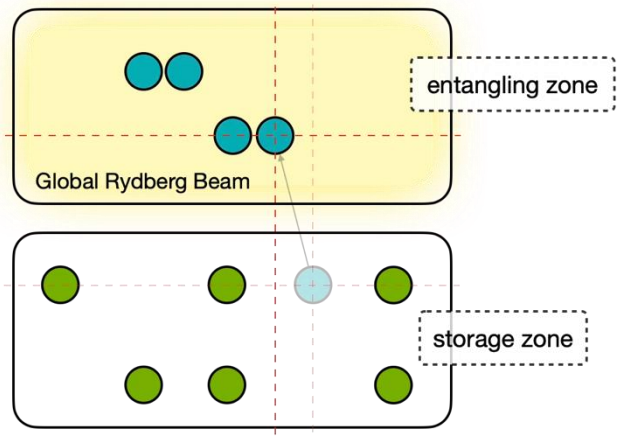
Scheduling: ASAP



Quantum compilation
Placing and routing

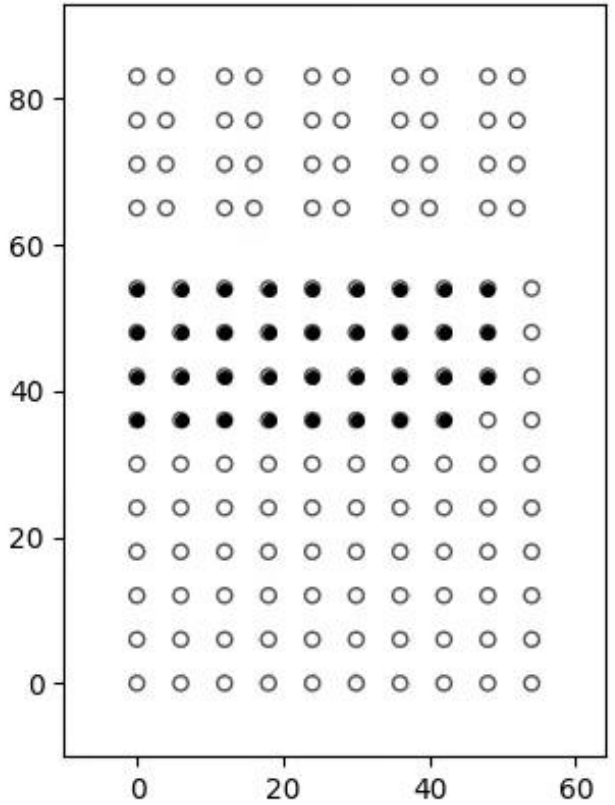
Architecture





physics?
physiCS!

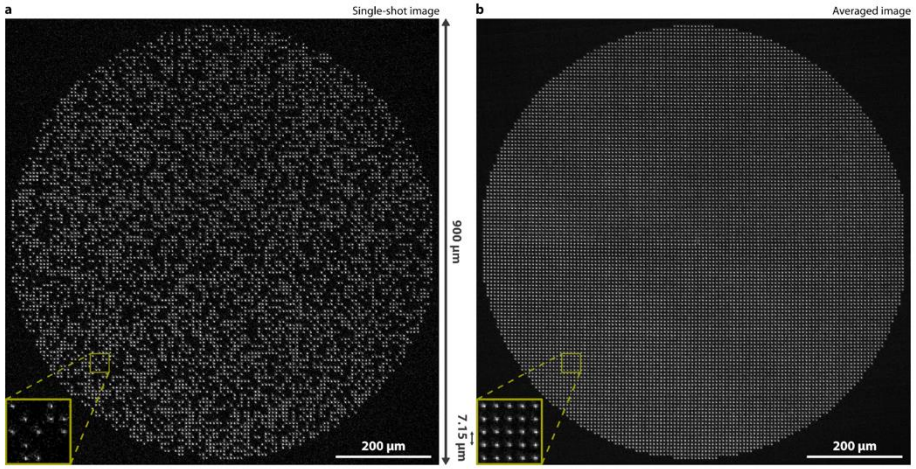
Example: Cat state preparation n35



Bluvstein, Dolev, et al. "Logical quantum processor based on reconfigurable atom arrays." *Nature* 626.7997 (2024): 58-65.

Summary
Advantages and drawbacks

Advantages
- Scalability



Manetsch, Hannah J., et al. "A tweezer array with 6100 highly coherent atomic qubits." *arXiv preprint arXiv:2403.12021* (2024).

- Connectivity
- Parallelism
- Small crosstalk
- High coherence time ~ s

Coherence time (T_2)	12.6(1) s
Global single-qubit gate RB fidelity	0.999834(2)

Drawback
- Individual addressing
- Gate operation time ~ us
- Readout time ~ ms
- Atom loss

IMPERIAL

北京量子信息科学研究院
Beijing Academy of Quantum Information Sciences

Thank you

北京量子院远程实习生

【工作内容】从事超导、中性原子、离子阱的量子编译与控制相关研究或辅助工作，要求具备一定的物理、数学背景。

【薪酬】4000 元/月（远程实习，很自由，时间自己安排）

【要求】在读本科/硕士/博士，对量子信息、量子编译等领域有浓厚兴趣；具备良好的学习能力、沟通能力与团队协作精神。

【简历投递】请将个人简历（含研究背景、学术成果或项目经历）、求职意向及相关材料发送至招聘邮箱（wangjb@baqis.ac.cn），邮件主题注明“应聘岗位+姓名+在读院校”。

【招聘流程】简历筛选-笔试/面试（远程或线下）-综合评估-录用通知。

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