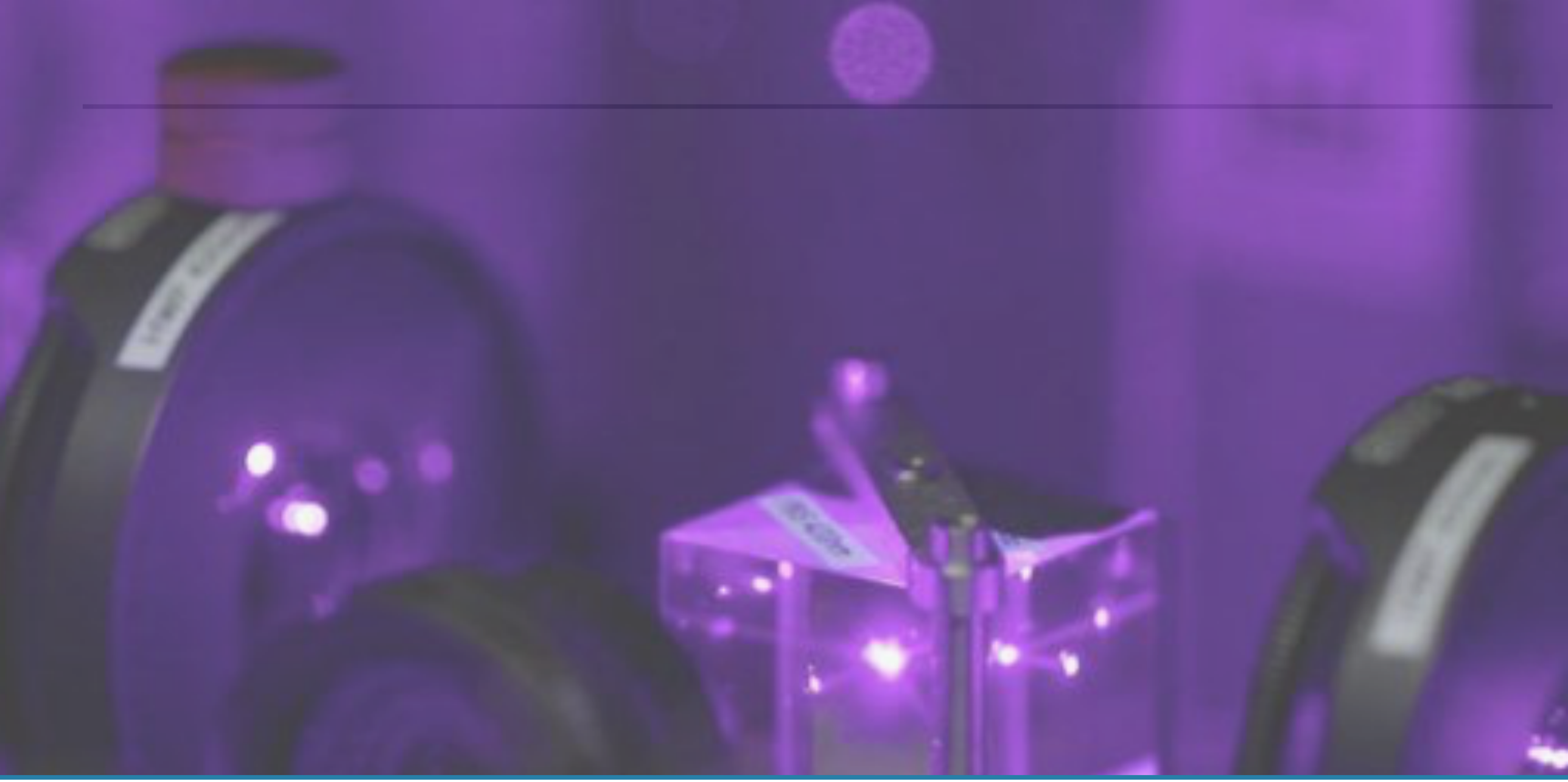

A DEMONSTRATION OF QUANTUM ERROR CORRECTION WITH NEUTRAL ATOMS

ARXIV:2312.03982, NATURE 626, 58 (2024)

WHAT IS THE SETTING?

- **Programmable quantum processor based** on encoded logical qubits operating with up to **280 physical qubits**
- Logical-level control and a "zoned architecture" in reconfigurable array of **neutral atom arrays**

Bluvstein, Evered, Geim, Li, Zhou, Manovitz, Ebadi, Cain, Kalinowski, Hangleiter, Bonilla Ataides, Maskara, Cong, Gao, Rodriguez, Karolyshyn, Semeghini, Gullans, Greiner, Vuletic, Lukin, arXiv:2312.03982 (2023)

- Presentation strongly inspired by great talk of **Vladan Vulecic**

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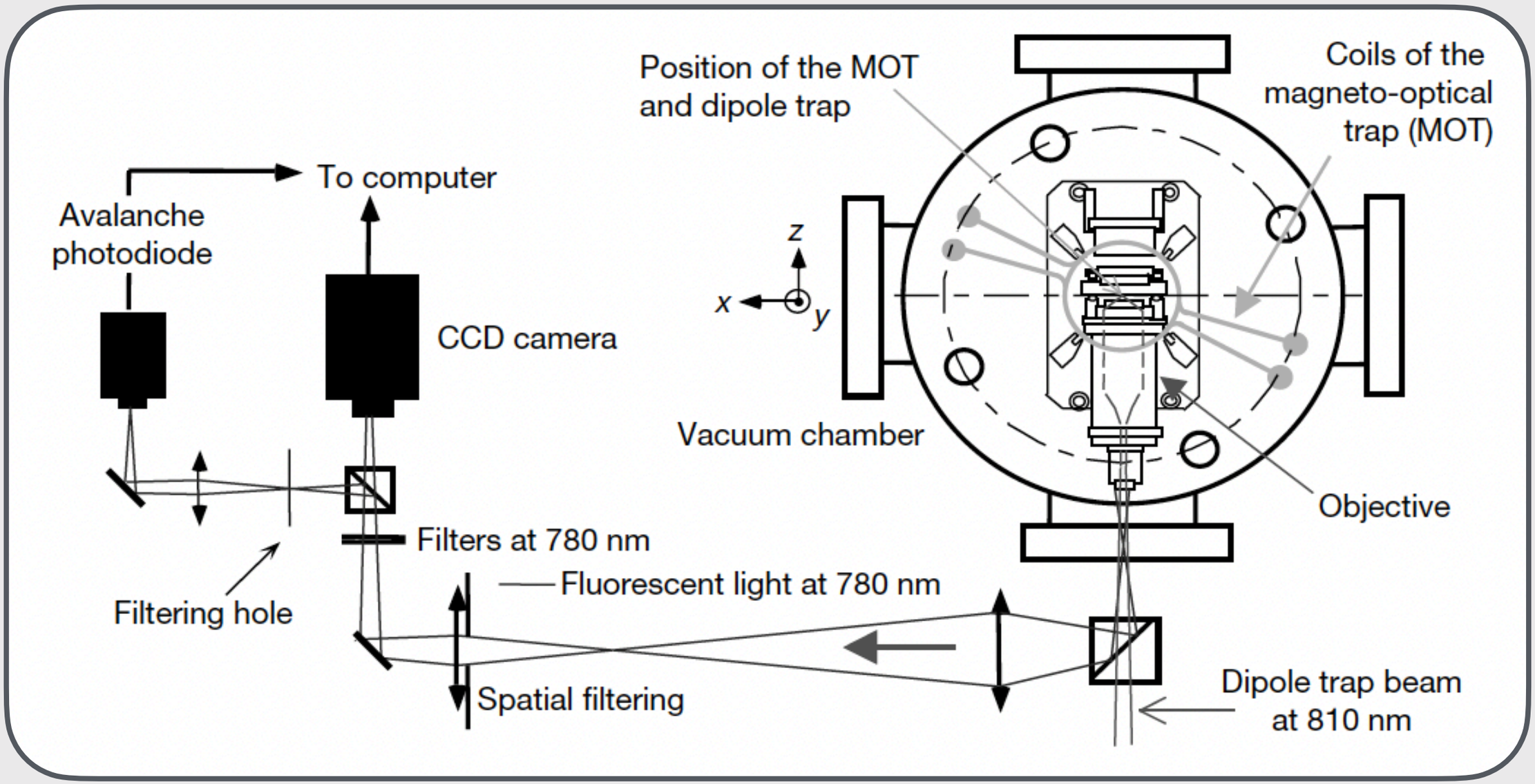
- Not with **optical lattices,** but **tweezers**

TRAPPING NEUTRAL ATOMS IN OPTICAL TWEEZERS

- One can **trap atoms** in strongly focused laser beams (tweezers)

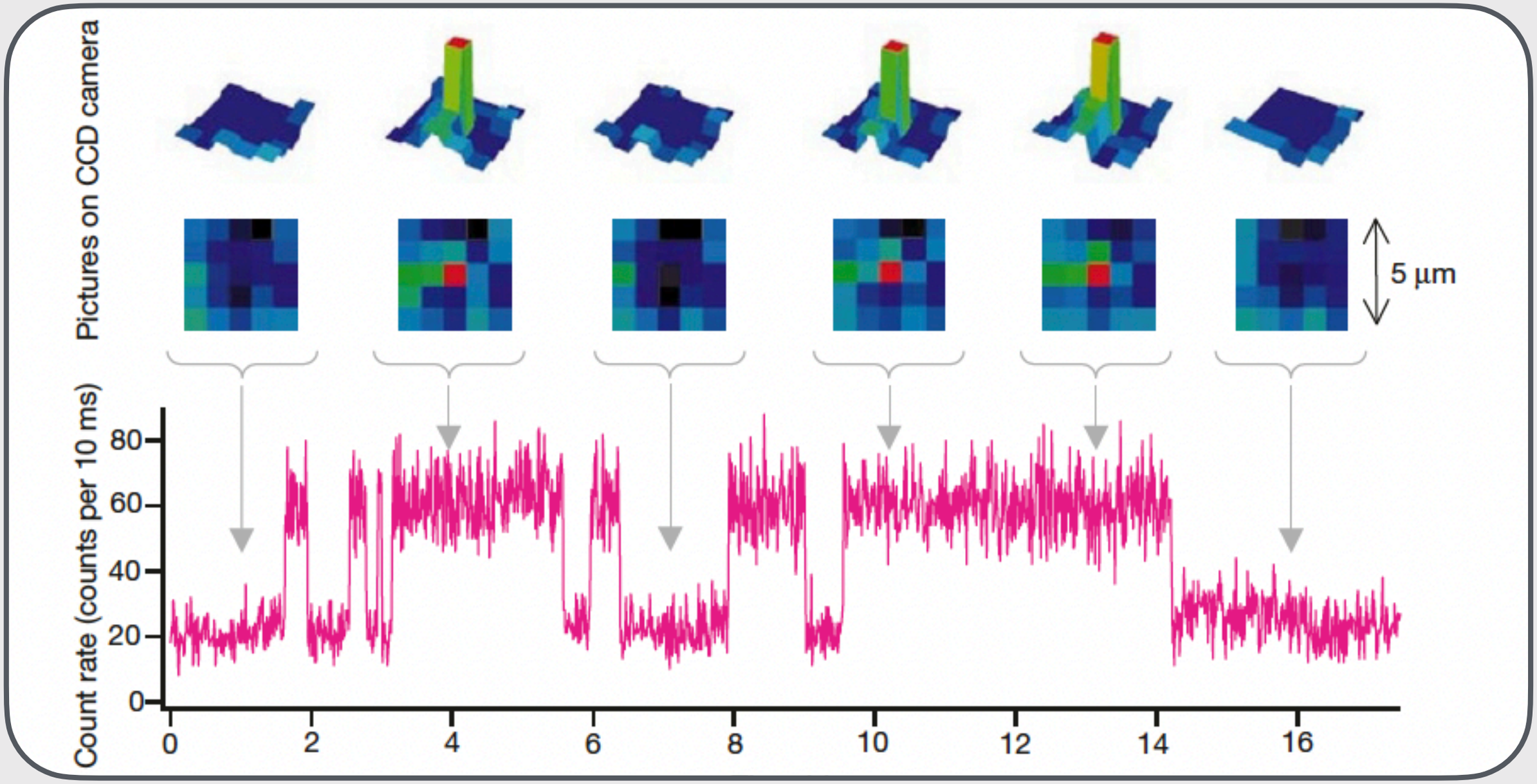


- Focusing objective with sub-micrometer resolution

Schlosser, Reymond, Protsenko, Grangier, Nature 411, 1024 (2001)

TRAPPING NEUTRAL ATOMS IN OPTICAL TWEEZERS

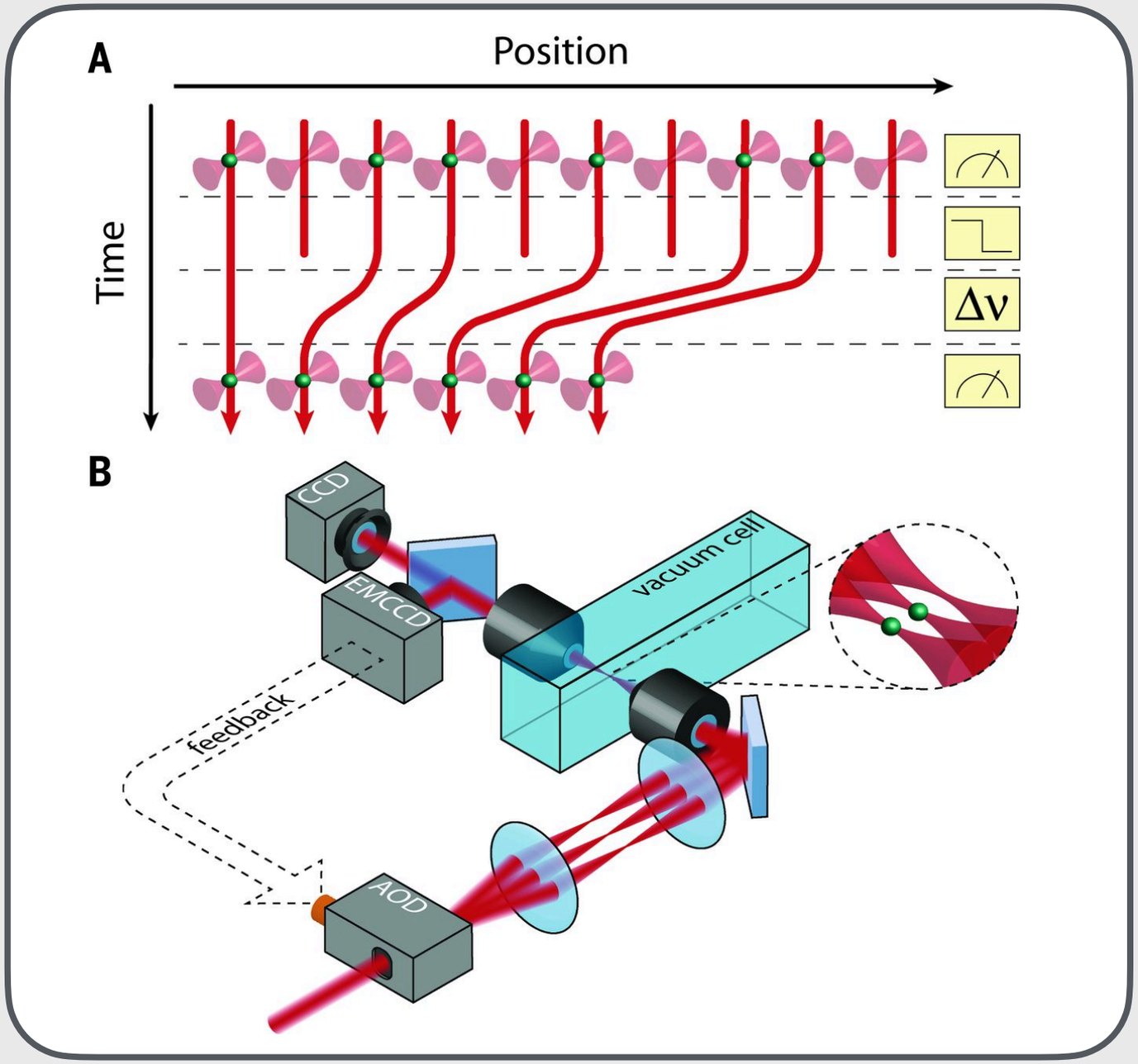
- Single atoms **detection**: Absence of two atoms in flourescence



Schlosser, Reymond, Protsenko, Grangier, Nature 411, 1024 (2001)

TWEEZER ARRAYS

- Make this a **defect-free array**: Deterministic loading is difficult

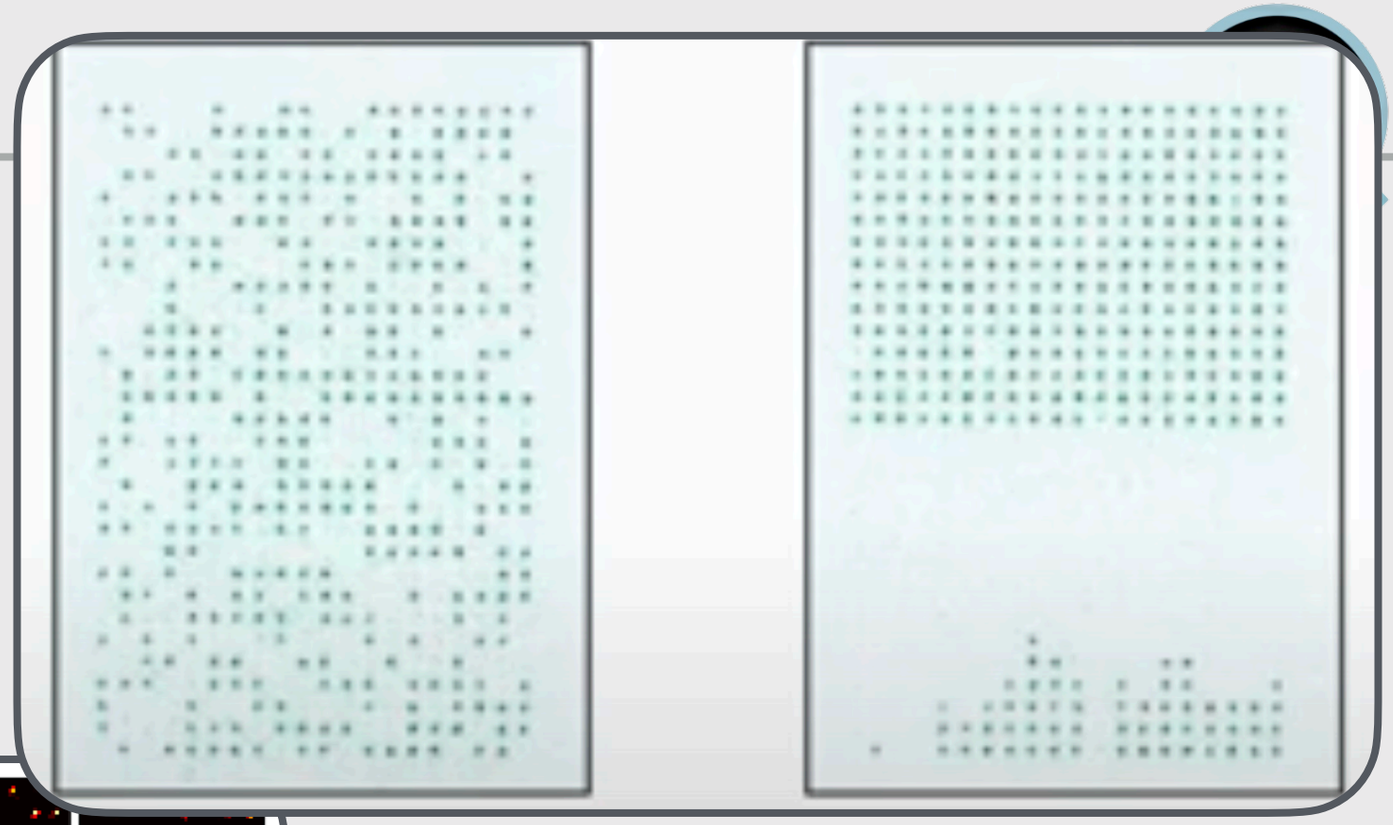


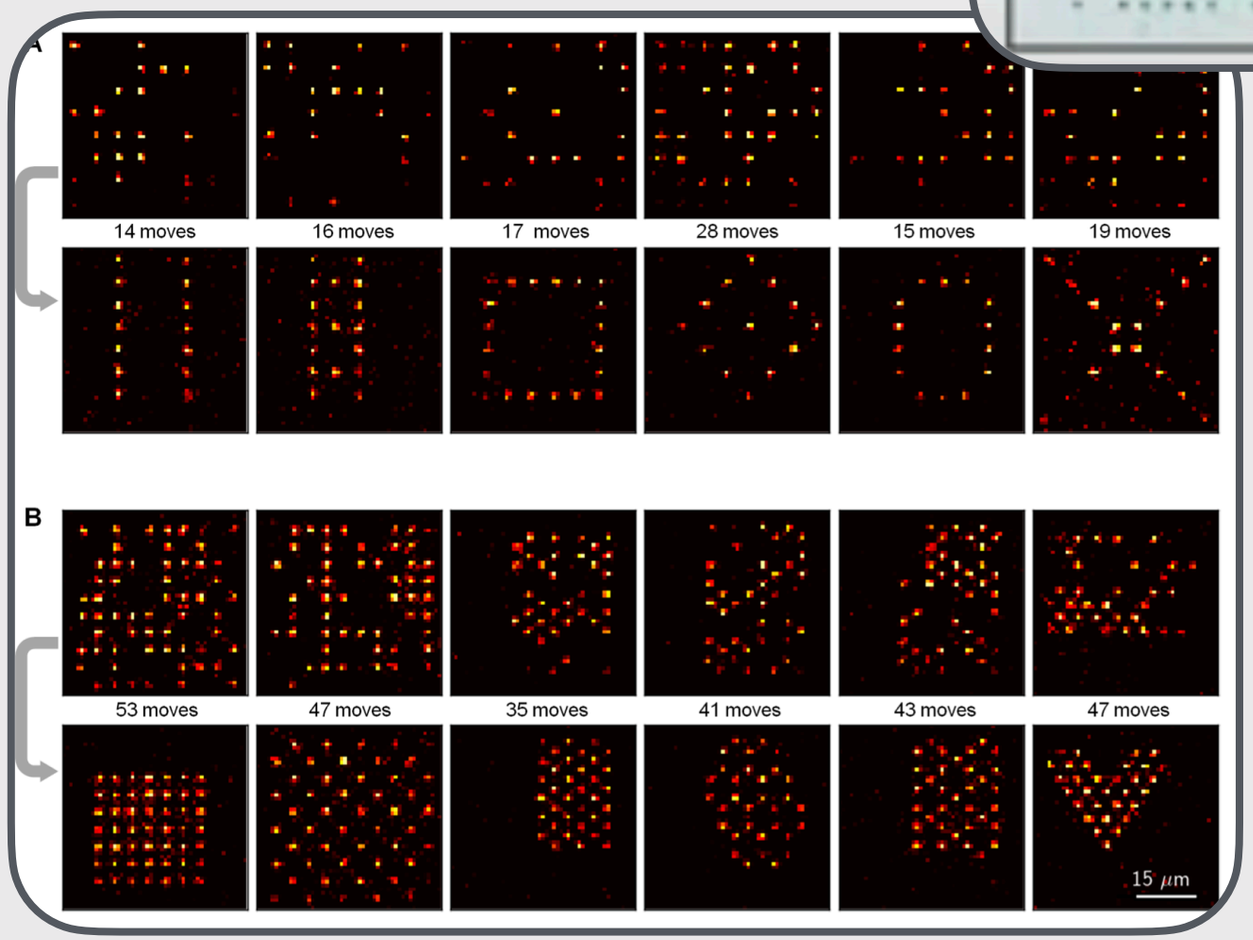
- Probability of trapping an atom a bit more than 50%
- Need detection and feedback
- Acousto-optical deflector to create **many traps**

Endres, Bernien, Keesling, Levine, Anschuetz, Krajenbrink, Senko, Vuletic, Greiner, Lukin, Science 354, 1024 (2016)

SORTING ATOMS

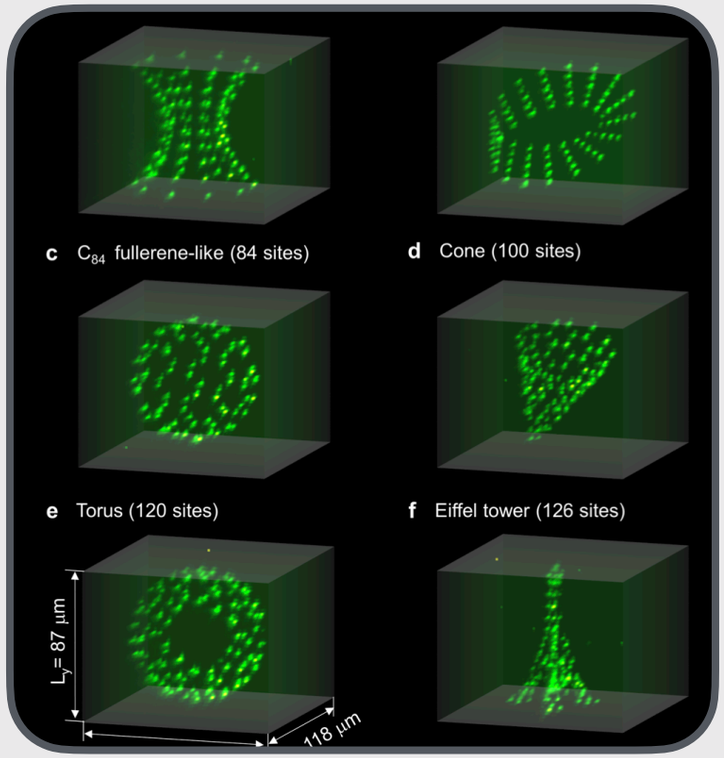
- Atoms can be **sorted** and made **defect-free**





Barredo, de Léséleuc, Lienhard, Lahaye, Browaeys,
Science 354, 1021 (2016)

- 3d structures in Paris



Barredo, Lienhard, de Léséleuc, Lahaye, Browaeys,
Nature 561, 79–82 (2018)

QUANTUM GATES

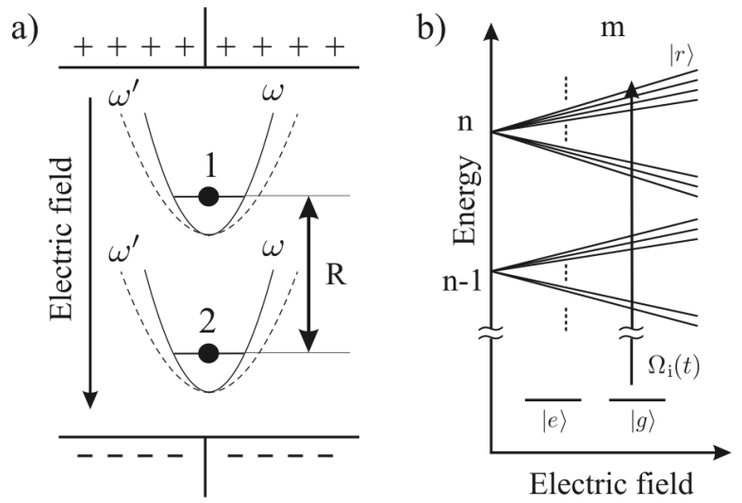
- For **quantum gates**, 2d architectures make most sense
- Need to **entangle atoms** a few µm away to optically resolve them
- Use highly excited **"Rydberg" states**
    - Electrons far away from nucleus
    - Tiny field can influence energy levels of system
    - Influences speed at which one can perform gates

QUANTUM GATES

- For **quantum gates**, 2d architectures make most sense
- Need to **entangle atoms** a few µm away to optically resolve them
- Use highly excited **"Rydberg" states**

  - Highly **excited** hydrogen-like states
  - Initially in Stark eigenstates, evolve with **dipole-dipole** potential

$$V_{\mathrm{dip}}(\mathbf{r}) = \frac{1}{4\pi\epsilon_0}\left[\frac{\mu_1 \cdot \mu_2}{|\mathbf{r}|^3} - 3\frac{(\mu_1 \cdot \mathbf{r})(\mu_2 \cdot \mathbf{r})}{|\mathbf{r}|^5}\right]$$



  - Large size, hence dipole moment
  - ~100 MHz interaction strength over 5 µm distance

Jaksch, Cirac, Zoller, Rolston, Côté, Lukin, Phys Rev Lett 85, 2208 (2000)

QUANTUM GATES

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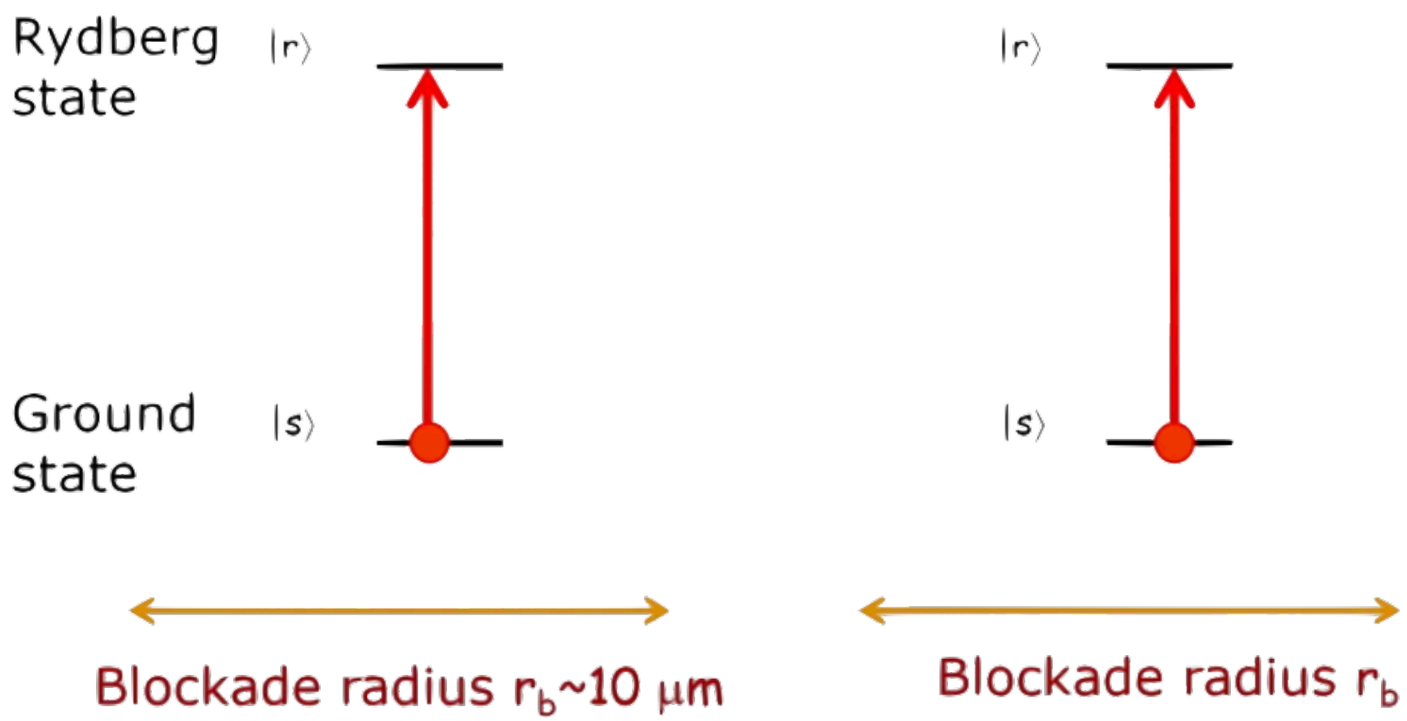
  - Concretely, use **Rydberg blockade**



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QUANTUM GATES

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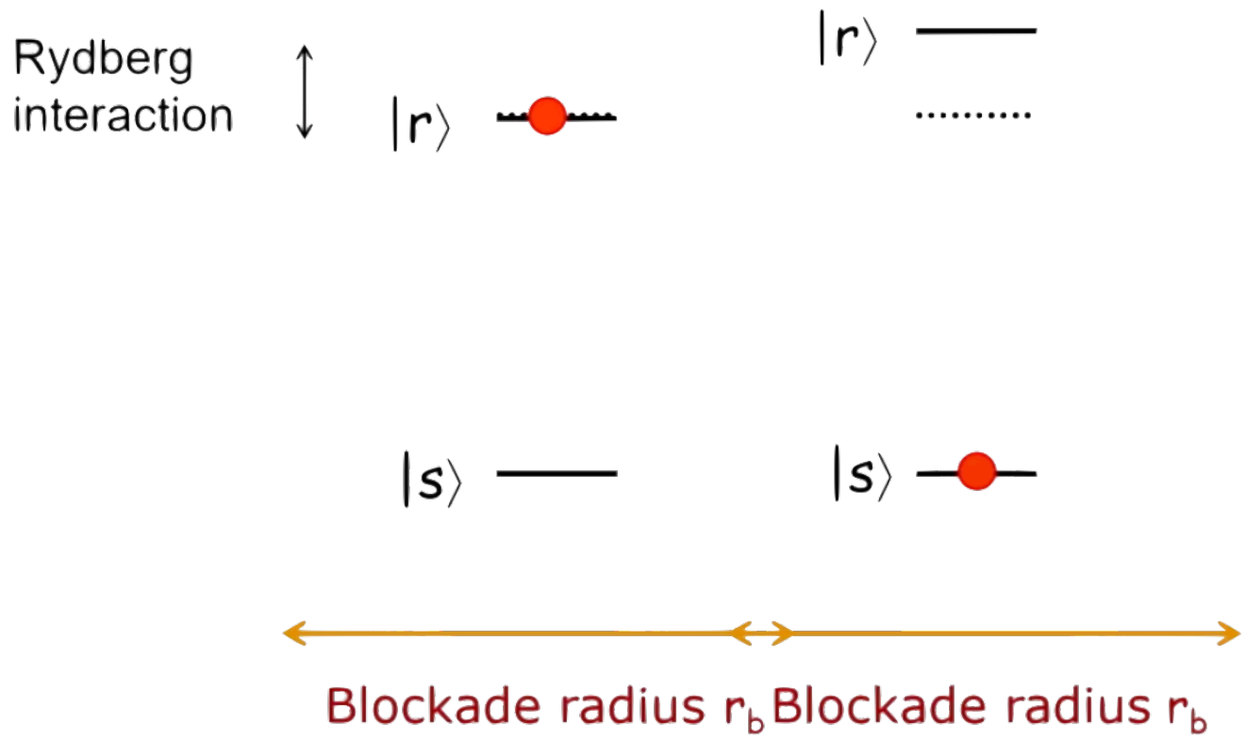
  - Only one atom can be **excited**



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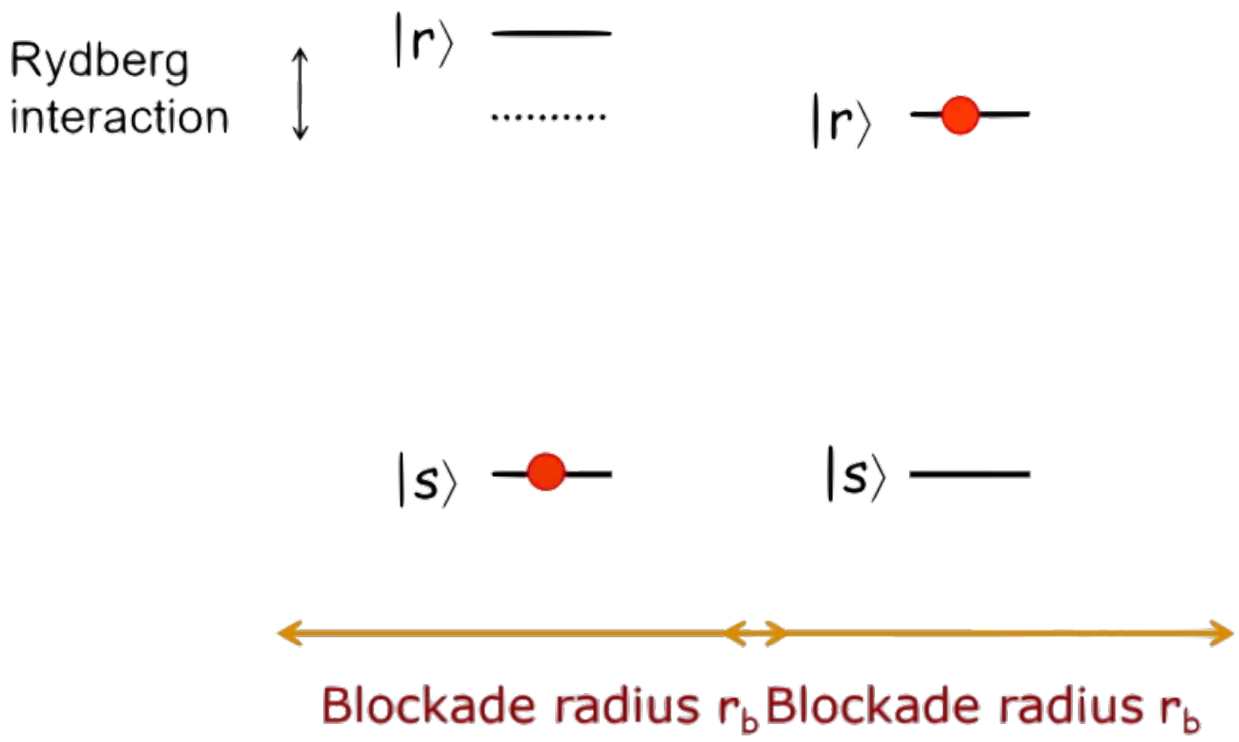

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QUANTUM GATES

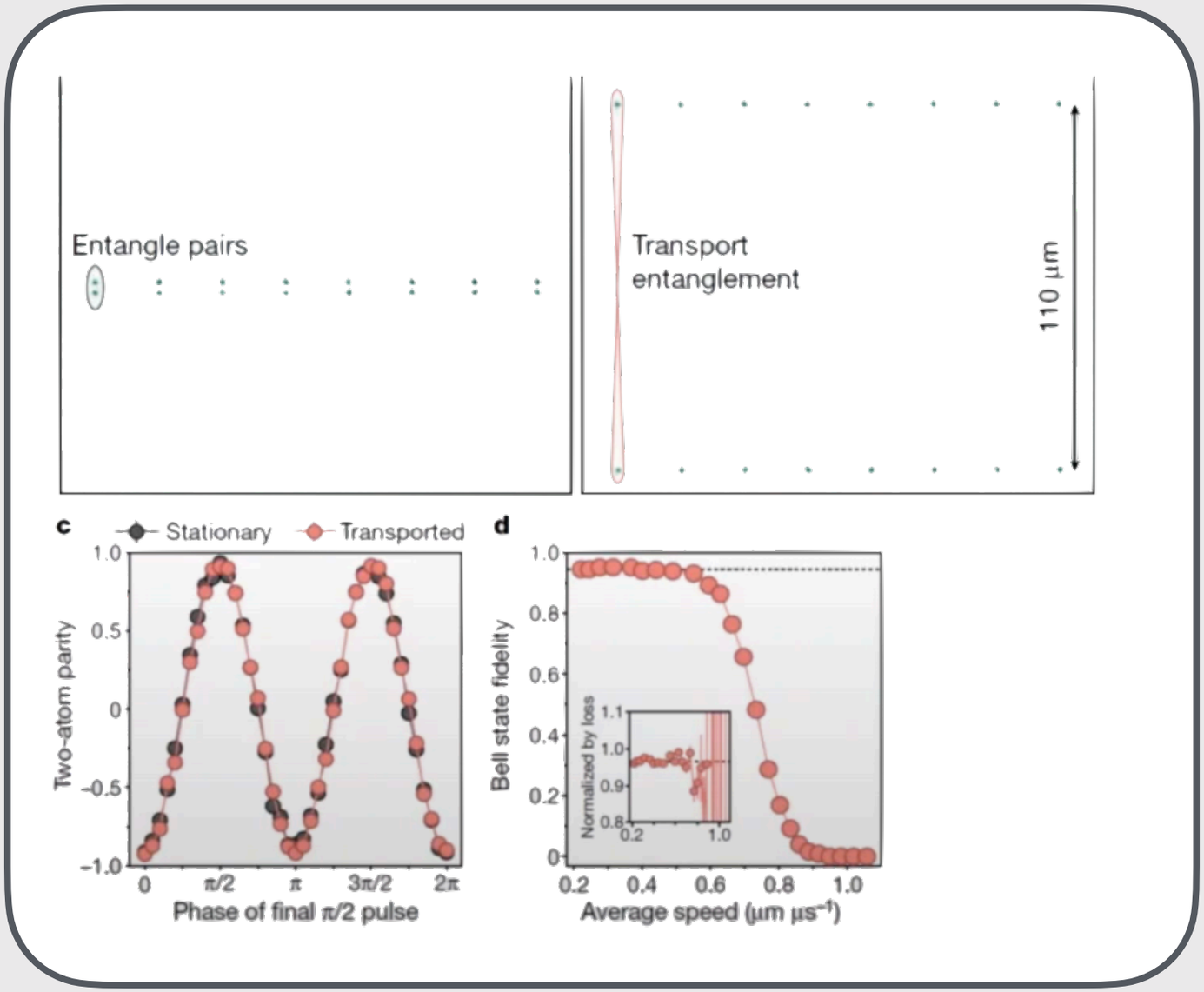
- For **quantum gates**, 2d architectures make most sense
- Need to **entangle atoms** a few µm away to optically resolve them
- Use highly excited **"Rydberg" states**

  - Can use **Rydberg-Rydberg interaction** for **fast quantum gates** over optically resolved distances

Levine, Keesling, Omran, Bernien, Schwartz, Zibrov, Endres, Greiner, Vuletic, Lukin, Phys Rev Lett 121, 123603 (2018)
Levine, Keesling, Semeghini, Omran, Wang, Ebadi, Bernien, Greiner, Vuletic, Pichler, Lukin, Phys Rev Lett 123, 170503 (2019)
Evered, Bluvstein, Kalinowski, Ebadi, Manowitz, Zhou, Li, Geim, Wang, Maskara, Levine, Semeghini, Greiner, Vuletic, Lukin, arXiv:2304.05420 (2023)

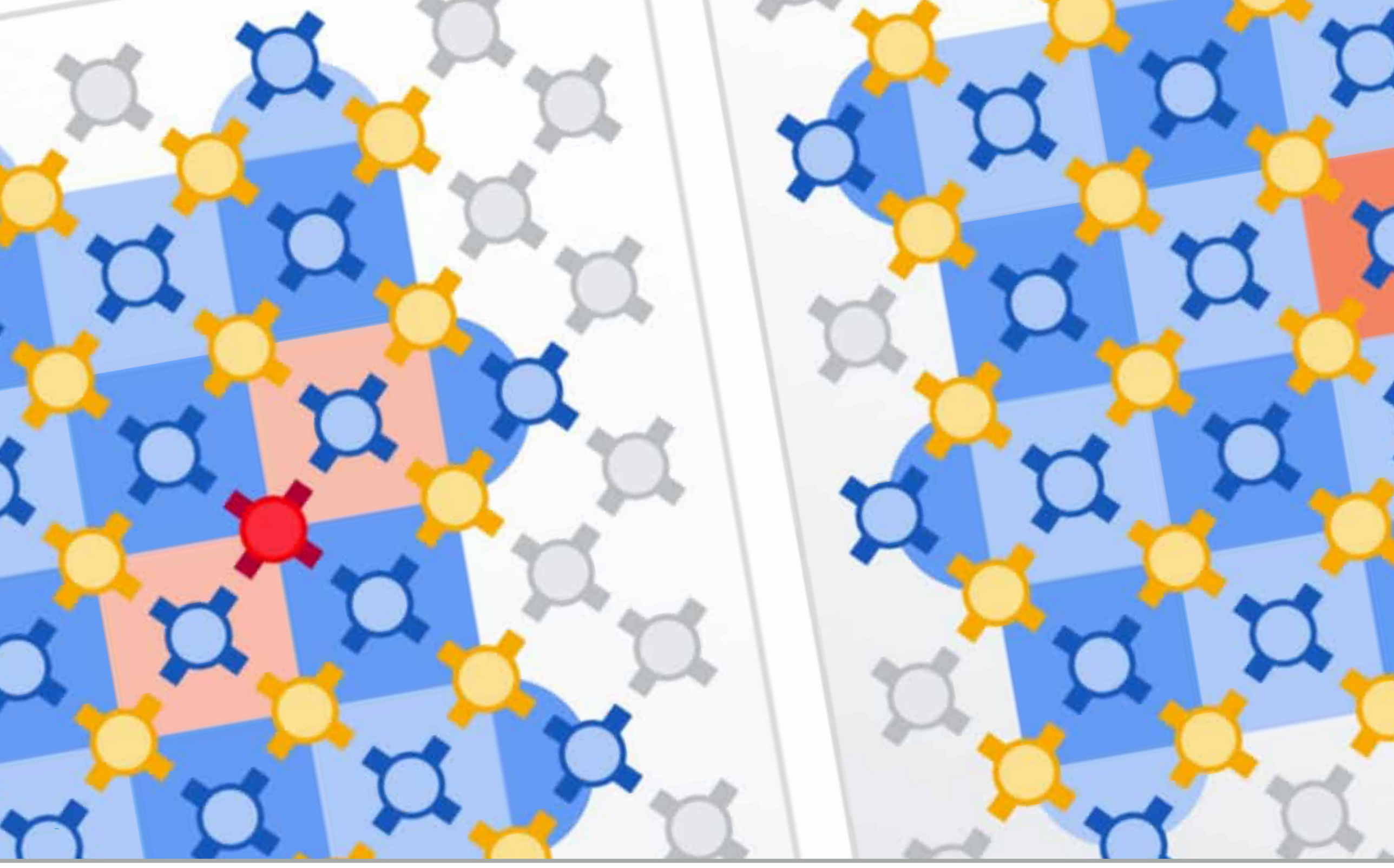
SHUTTLING ATOMS AROUND

- **Transporting** entanglement



- Little deterioration of the **entanglement** of a Bell pair
- **Non-local connections** (see qLDPC codes)

Bluvstein, Evered, Geim, Li, Zhou, Manovitz, Ebadi, Cain, Kalinowski, Hangleiter, Bonilla Ataides, Maskara, Cong, Gao, Rodriguez, Karolyshyn, Semeghini, Gullans, Greiner, Vuletic, Lukin, arXiv:2312.03982 (2023)



QUANTUM ERROR CORRECTION

QUANTUM ERROR CORRECTION

- They have used this setup for **quantum error correction**

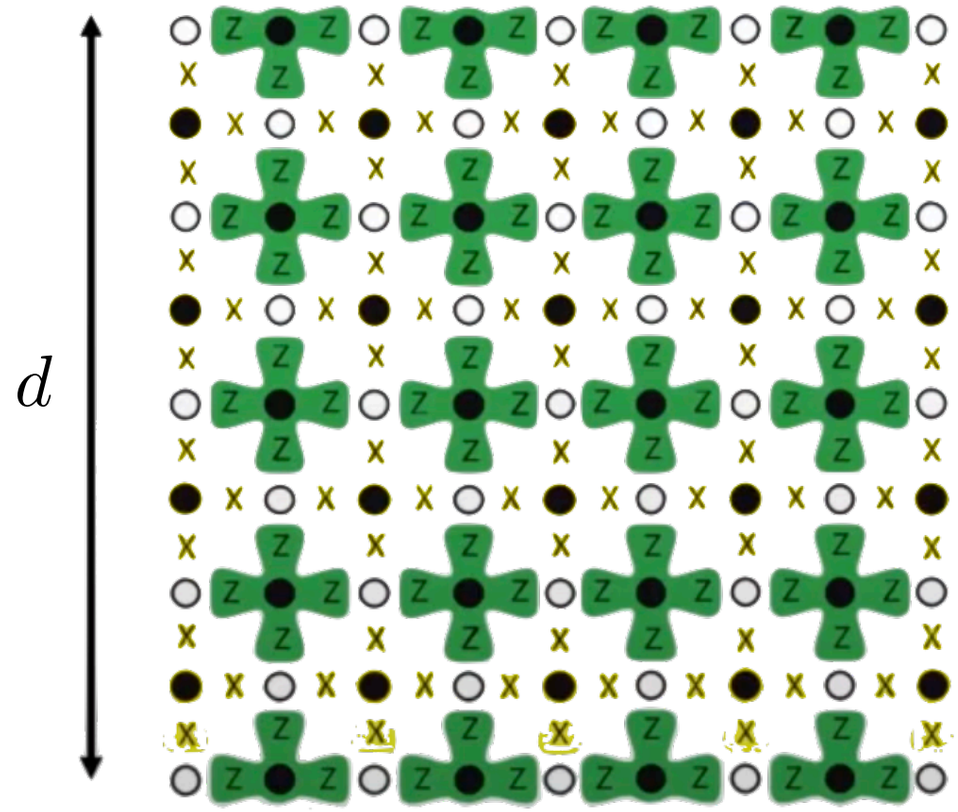
  - Encoded logical qubits operating with up to **280 physical qubits**

Bluvstein, Evered, Geim, Li, Zhou, Manovitz, Ebadi, Cain, Kalinowski, Hangleiter, Bonilla Ataides, Maskara, Cong, Gao, Rodriguez, Karolyshyn, Semeghini, Gullans, Greiner, Vuletic, Lukin, arXiv:2312.03982 (2023)

SURFACE CODE

- Realized **surface code** with distance $d = 3$ up to $d = 7$

- Surface code in 2d

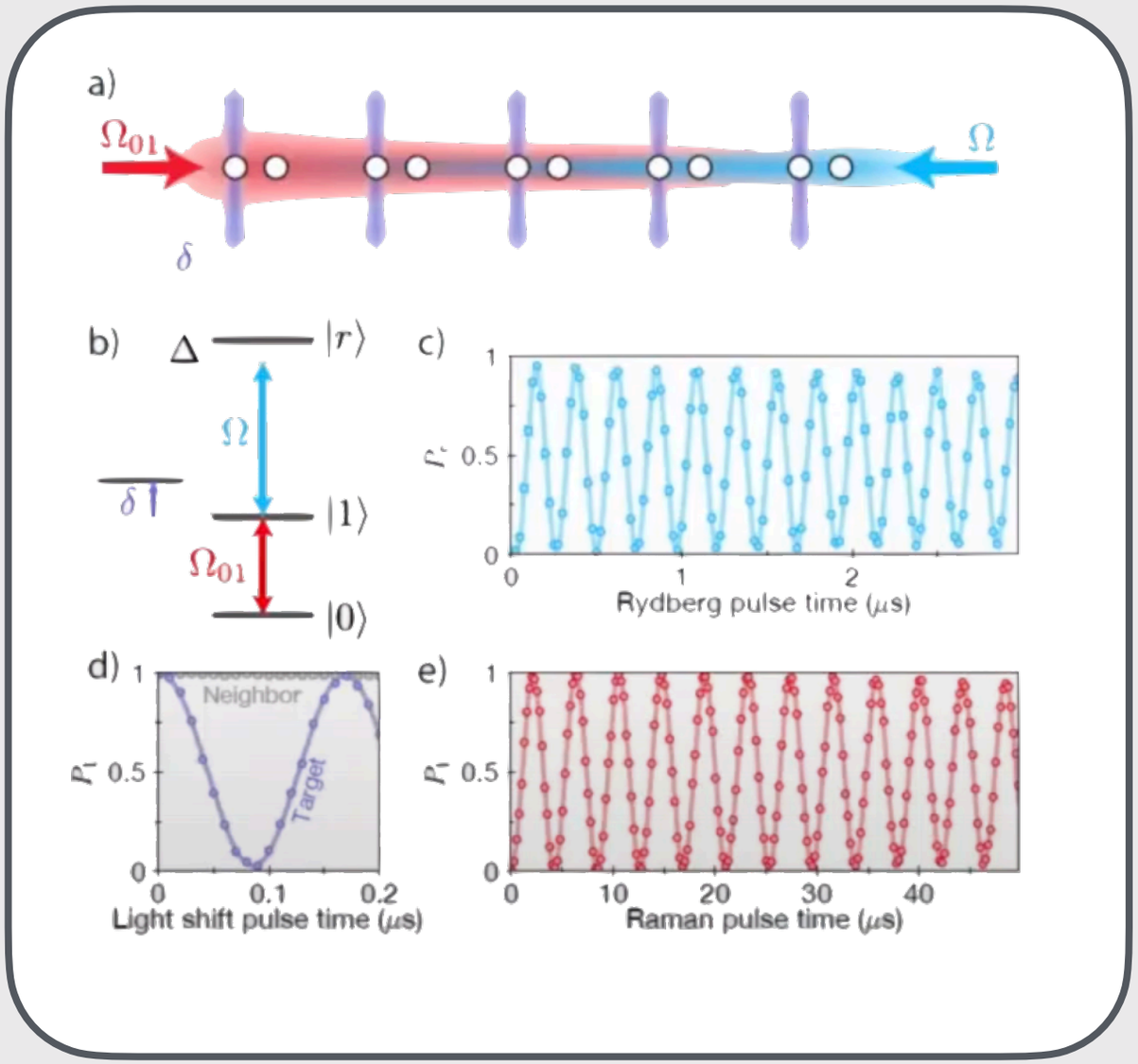


- High threshold around 1%
- Logical error

$$\approx (p_{\text{phys}}/p_{\text{th}})^{d/2}$$

SURFACE CODE

- Improved **single qubit gates** (driven by laser)

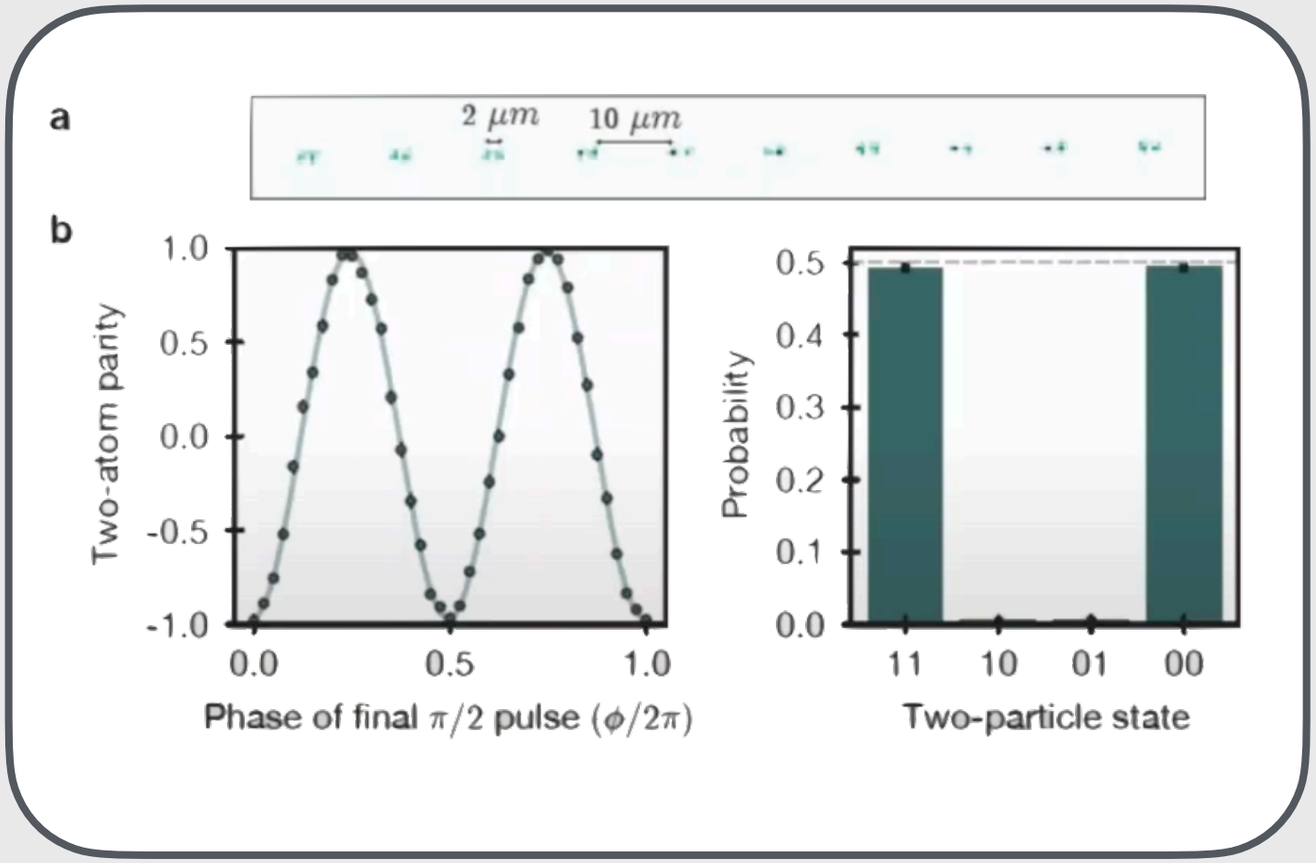


- Single-qubit average gate fidelities via randomized benchmarking >0.9998

Levine, Bluvstein, Keesling, Wang, Ebadi, Semeghini, Omran, Greiner, Vuletic, Lukin, Phys Rev A 105, 032618 (2022)

SURFACE CODE

- Improved **two qubit gates** (run in parallel on 30 atoms)



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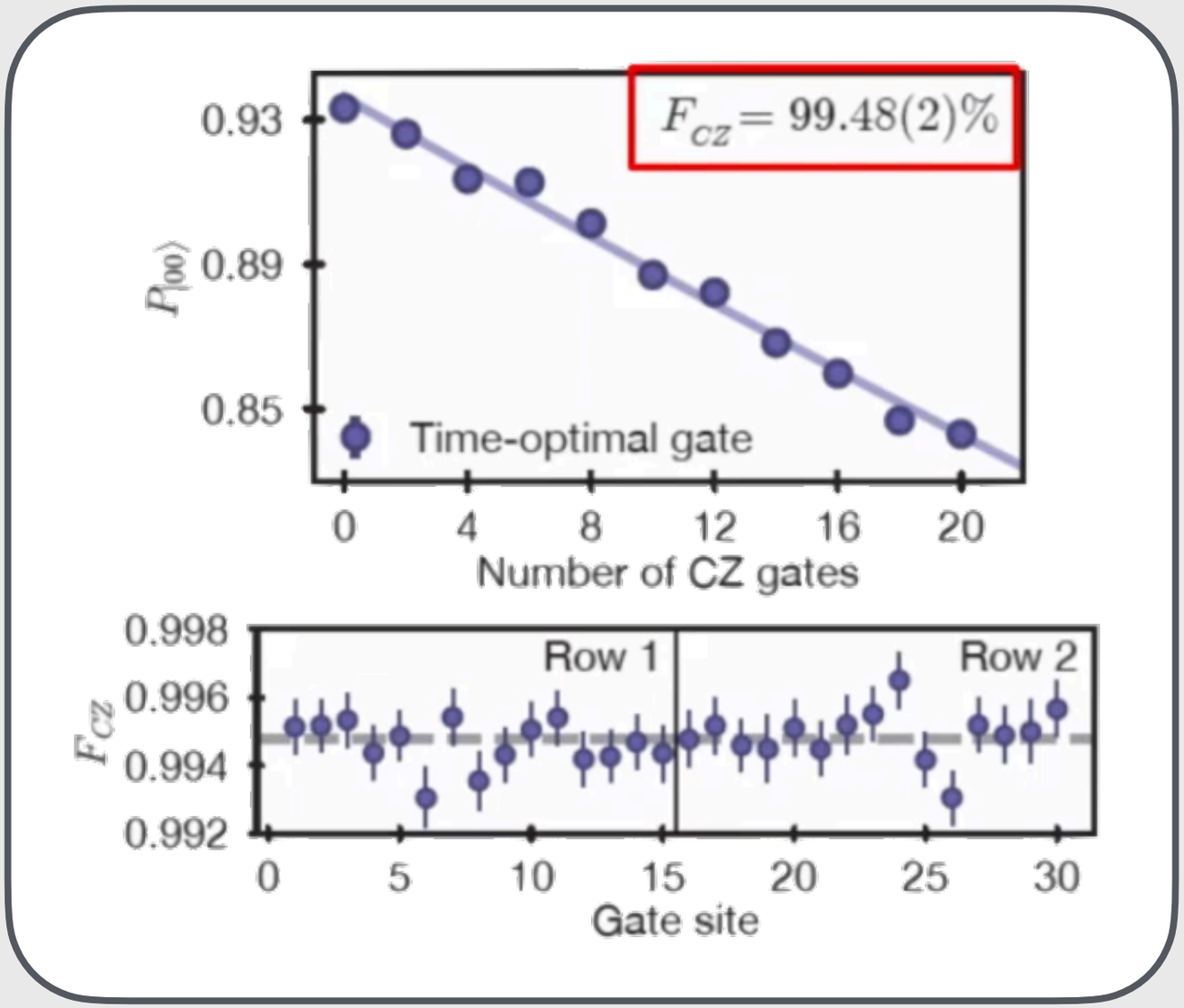
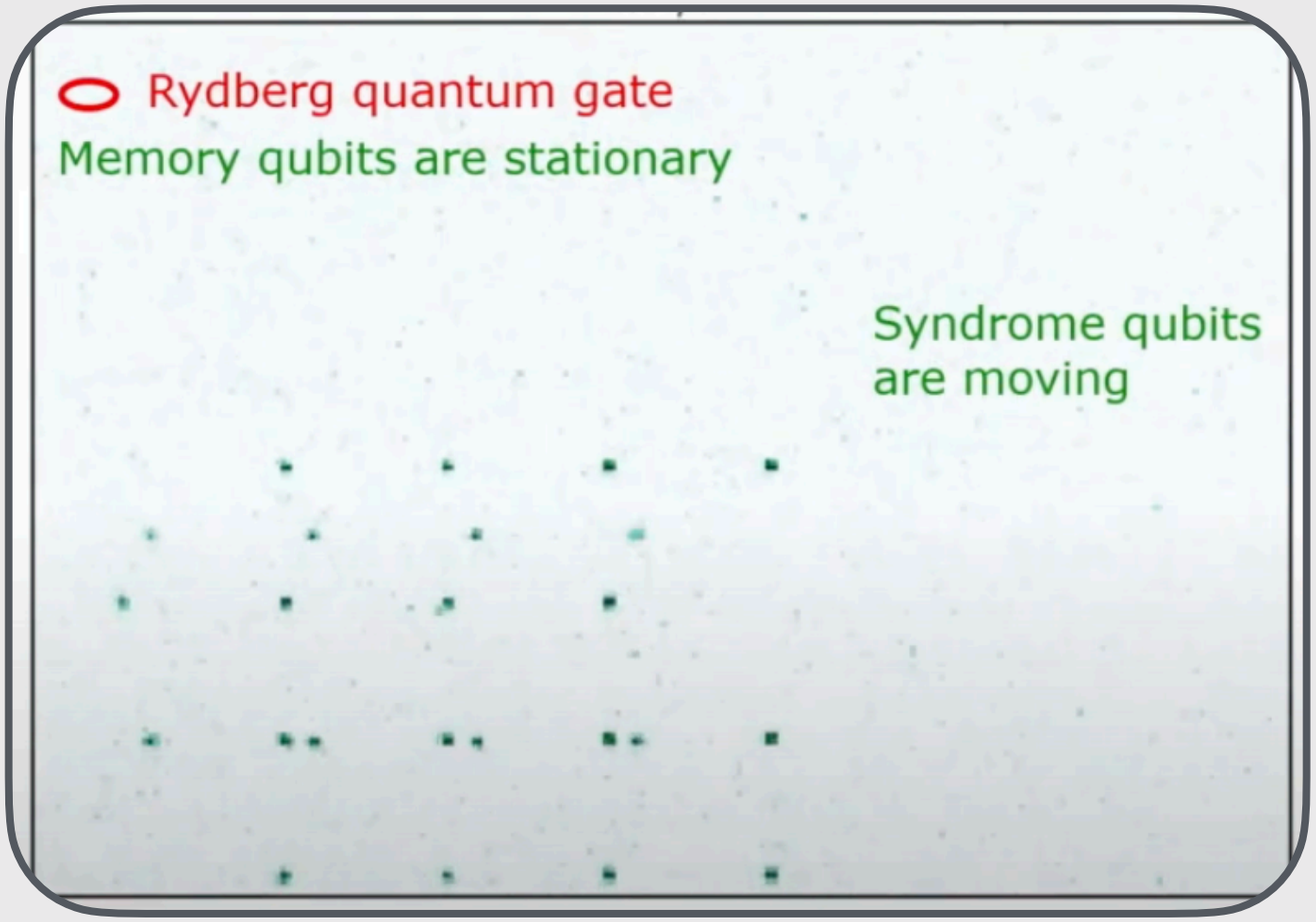


- Two-qubit average gate fidelities via randomized benchmarking >0.9948
- Below threshold

Levine, Bluvstein, Keesling, Wang, Ebadi, Semeghini, Omran, Greiner, Vuletic, Lukin, Phys Rev A 105, 032618 (2022)

SURFACE CODE

- Implementation of a **surface and toric code**



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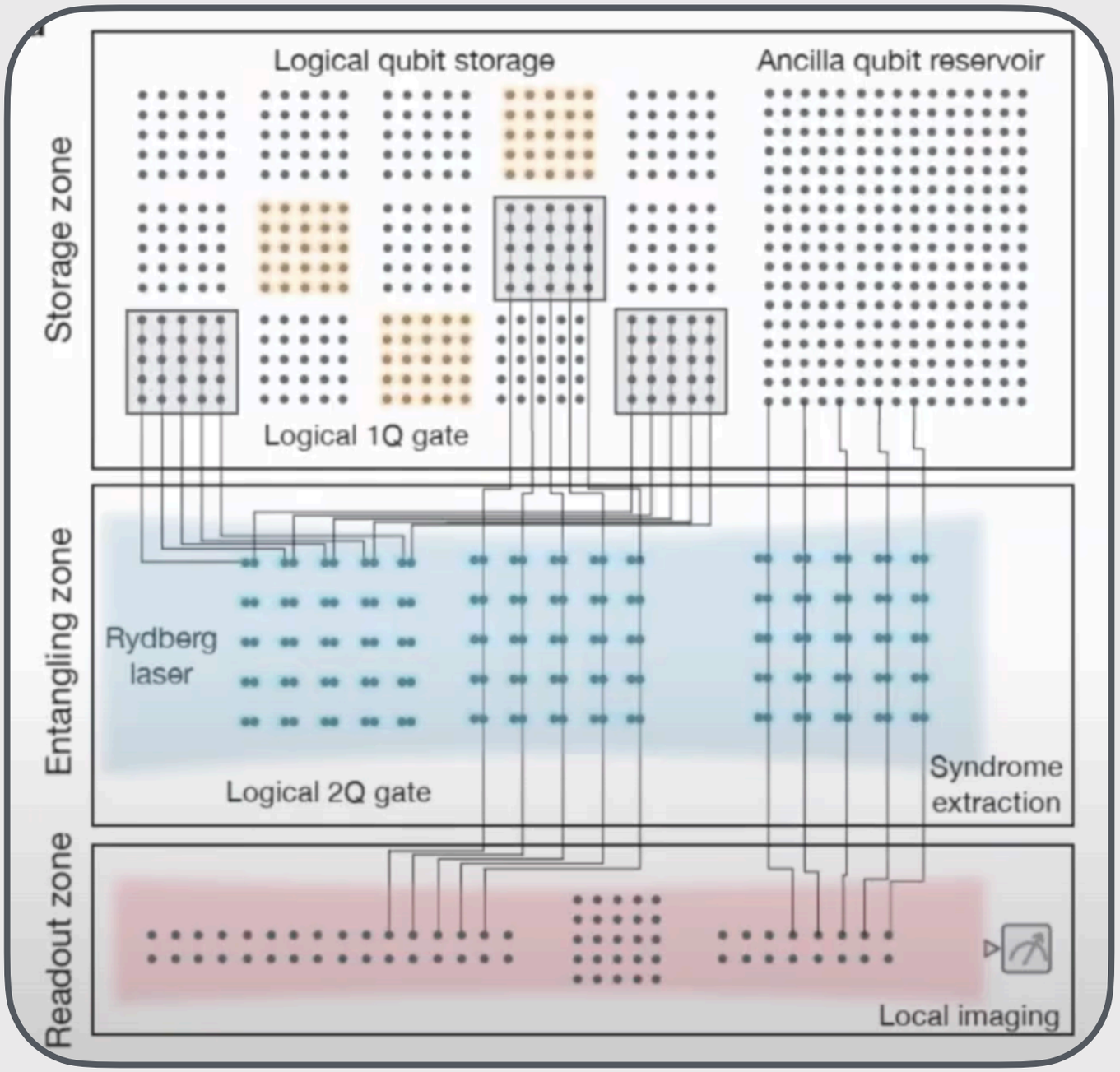
Bluvstein, Evered, Geim, Li, Zhou, Manovitz, Ebadi, Cain, Kalinowski, Hangleiter, Bonilla Ataides, Maskara, Cong, Gao, Rodriguez, Karolyshyn, Semeghini, Gullans, Greiner, Vuletic, Lukin, arXiv:2312.03982 (2023)

THREE ZONES

- Three zones for logical **quantum information processing**

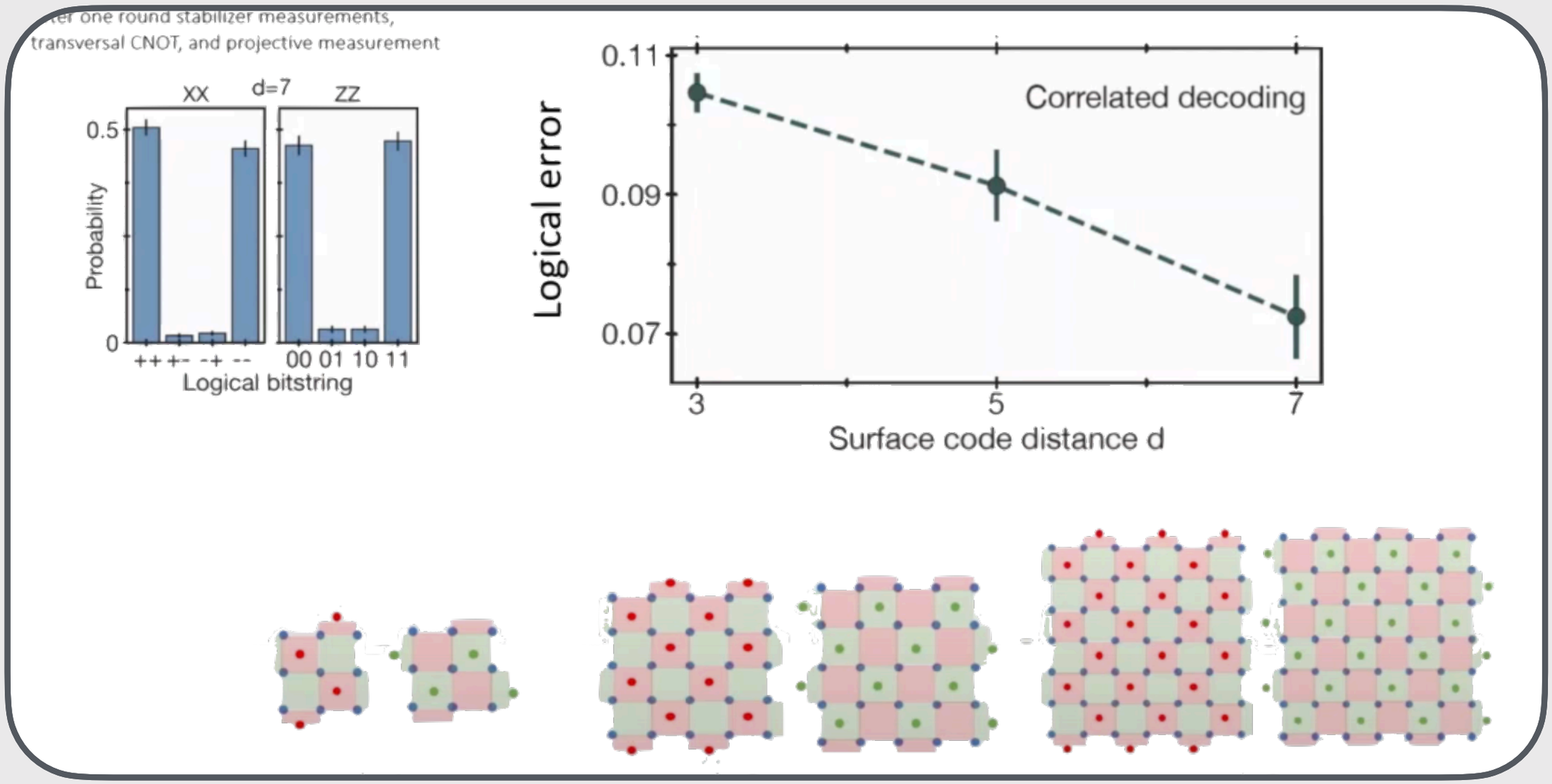


- Storage zone
- Rydberg entangling zone
- Readout zone

Bluvstein, Evered, Geim, Li, Zhou, Manovitz, Ebadi, Cain, Kalinowski, Hangleiter, Bonilla Ataides, Maskara, Cong, Gao, Rodriguez, Karolyshyn, Semeghini, Gullans, Greiner, Vuletic, Lukin, arXiv:2312.03982 (2023)

LOGICAL QUANTUM GATE

- **Logical CNOT** with surface code

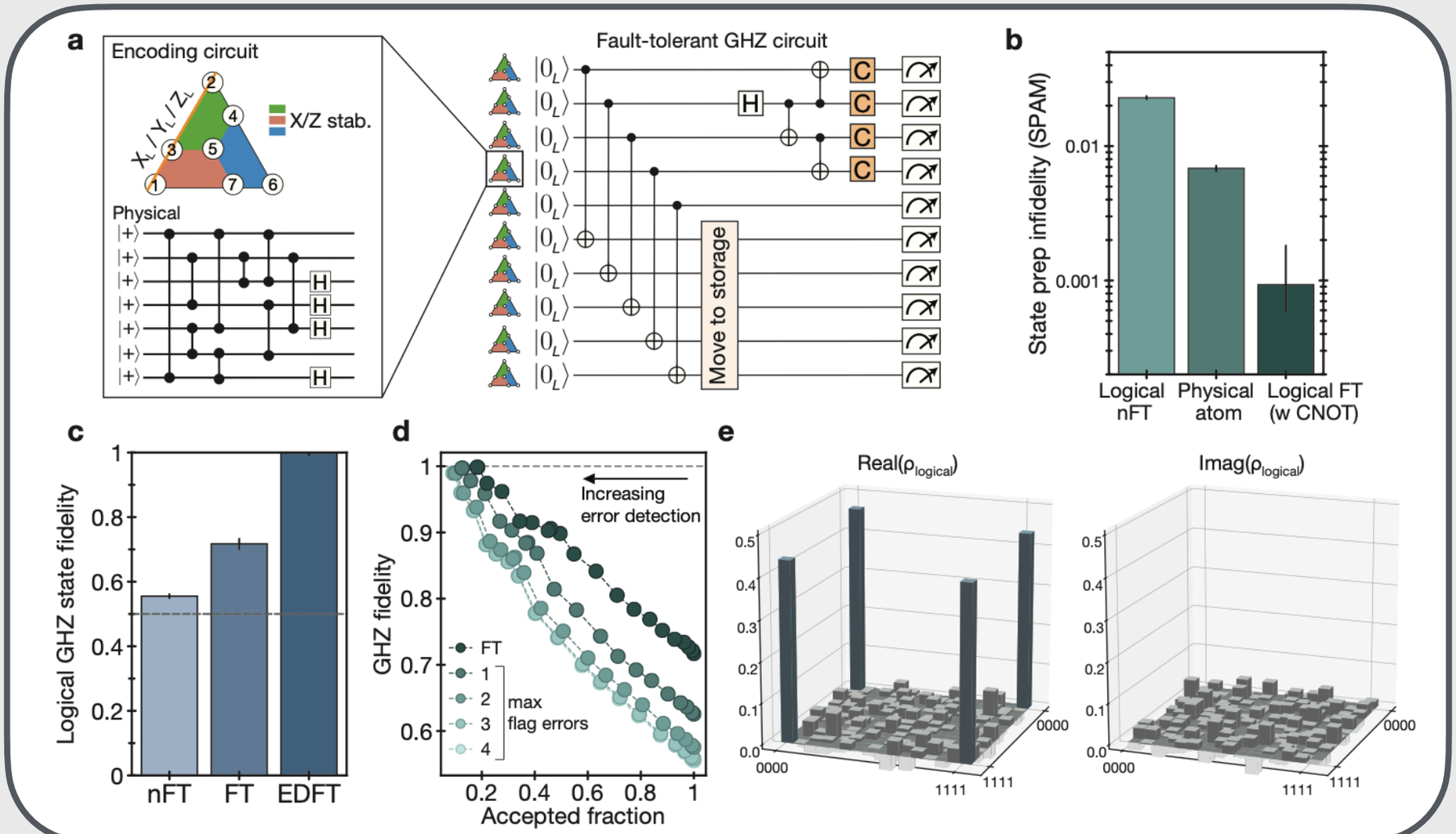


- **Improved logical error** with code distance

Bluvstein, Evered, Geim, Li, Zhou, Manovitz, Ebadi, Cain, Kalinowski, Hangleiter, Bonilla Ataides, Maskara, Cong, Gao, Rodriguez, Karolyshyn, Semeghini, Gullans, Greiner, Vuletic, Lukin, arXiv:2312.03982 (2023)

LOGICAL GHZ STATE PREPARATION

- **Logical GHZ state** of five qubits (Steane code, color code)



- **Error detection** rather than correction
- **Repeating,** 40 color codes with 280 physical qubits

Bluvstein, Evered, Geim, Li, Zhou, Manovitz, Ebadi, Cain, Kalinowski, Hangleiter, Bonilla Ataides, Maskara, Cong, Gao, Rodriguez, Karolyshyn, Semeghini, Gullans, Greiner, Vuletic, Lukin, arXiv:2312.03982 (2023)

IQP CIRCUIT SAMPLING

- **IQP circuits** are hard to sample from (in $\|.\|_{l_1}$ -distance)

  - Start in $|+\rangle$ state vectors
  - Apply unitaries diagonal in the computational basis
  - Measurements in the Hadamard basis

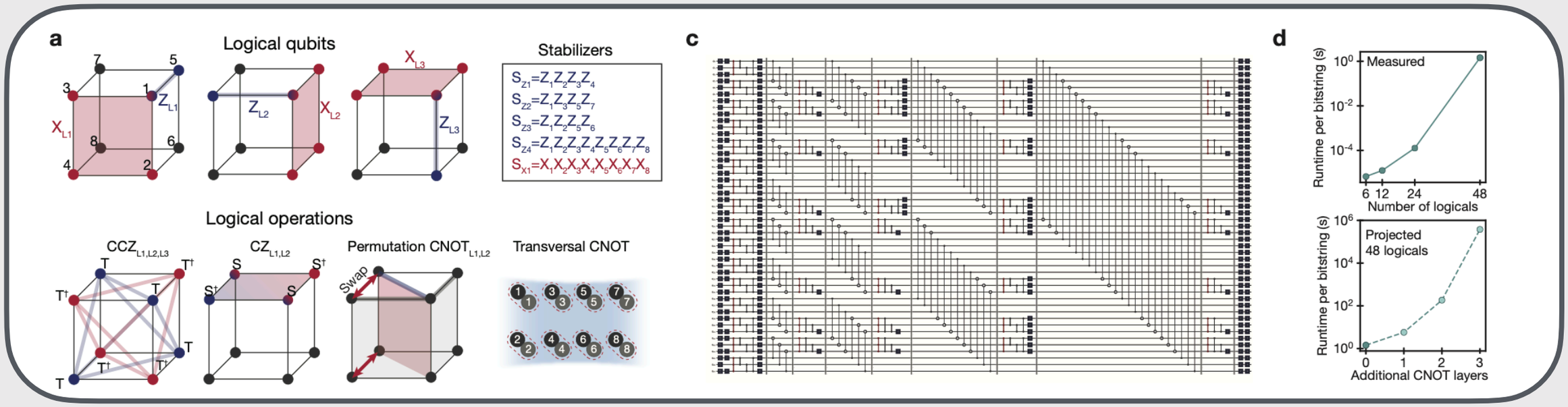
Bremner, Montanaro, Shepherd, Phys Rev Lett 117, 080501 (2016)
Hangleiter, Eisert, Rev Mod Phys 95, 035001 (2023)

- Maybe not as hard for **constant noise** (poly-time classical simulation of noisy IQP circuits with constant depth)

Rajakumar, Watson, Liu, arXiv:2403.14607 (2024)
Same day as Mele, Angrisani, Ghosh, Khatri, Eisert, França, Quek, arXiv:2403.13927 (2024)

ENCODED IQP CIRCUIT SAMPLING

- **Encoded sampling** with 12 logical qubits in [[8,3,2]] hypercube code
- [[8,3,2]] block codes can transversally realize {CCZ, CZ, Z, CNOT} gates within each block, and transversal CNOTs between blocks
- [[8,3,2]] codes are entangled on 4d hypercubes



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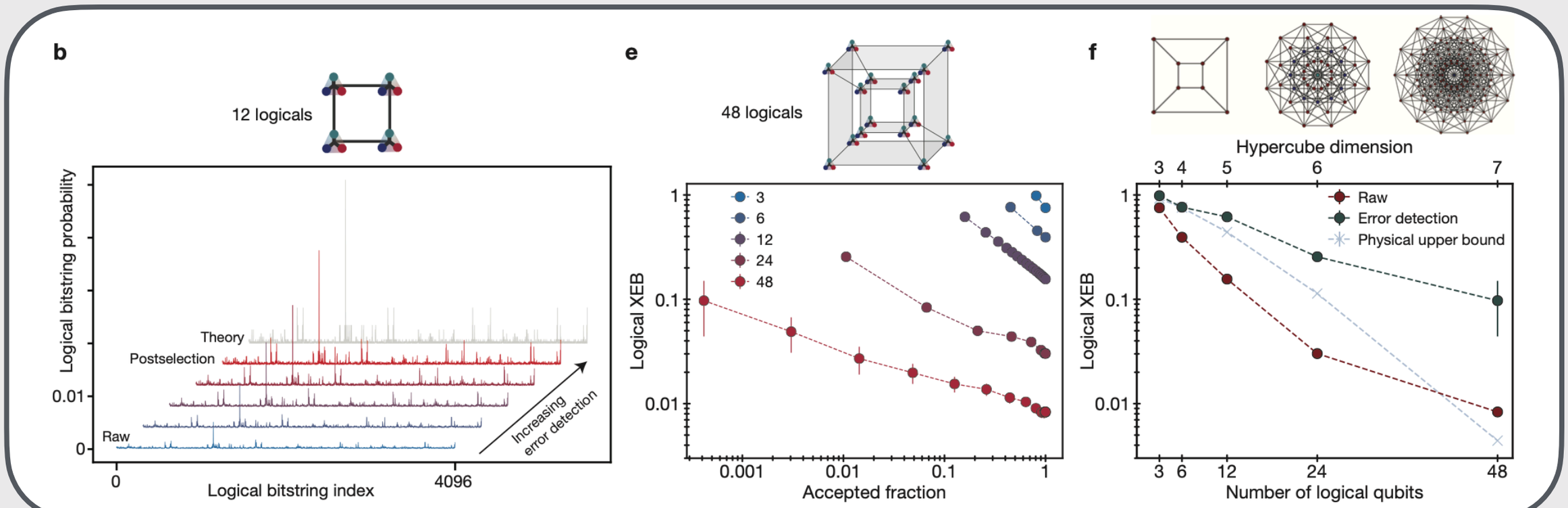

- **Logical XEB benchmarking**

Bluvstein, Evered, Geim, Li, Zhou, Manovitz, Ebadi, Cain, Kalinowski, Hangleiter, Bonilla Ataides, Maskara, Cong, Gao, Rodriguez, Karolyshyn, Semeghini, Gullans, Greiner, Vuletic, Lukin, arXiv:2312.03982 (2023)

UPSHOT

- What they have done with up to 280 physical and qubits
  - Toric and surface code preparation
  - Logical quantum gates
  - Logical GHZ state preparation
  - Encoded sampling

Bluvstein, Evered, Geim, Li, Zhou, Manovitz, Ebadi, Cain, Kalinowski, Hangleiter, Bonilla Ataides, Maskara, Cong, Gao, Rodriguez, Karolyshyn, Semeghini, Gullans, Greiner, Vuletic, Lukin, arXiv:2312.03982 (2023)

UPSHOT

- What they have done
  - Toric and surface code preparation
  - Logical quantum gates
  - Logical GHZ state preparation
  - Encoded sampling
- What they have not done - or I missed it
  - Realize qLDPC codes

THANKS, LET US DISCUSS MORE

Bluvstein, Evered, Geim, Li, Zhou, Manovitz, Ebadi, Cain, Kalinowski, Hangleiter, Bonilla Ataides, Maskara, Cong, Gao, Rodriguez, Karolyshyn, Semeghini, Gullans, Greiner, Vuletic, Lukin, arXiv:2312.03982 (2023)