

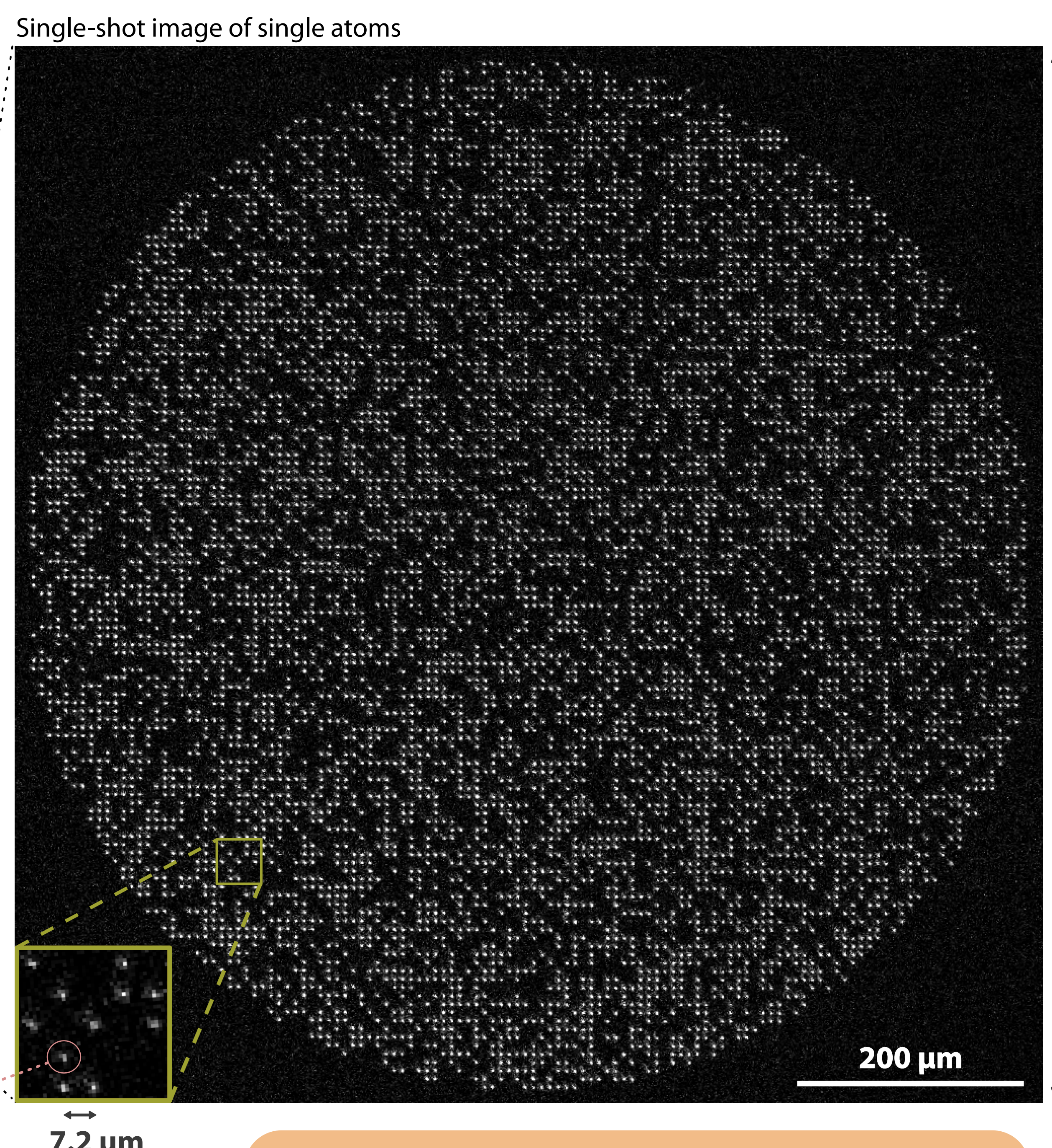
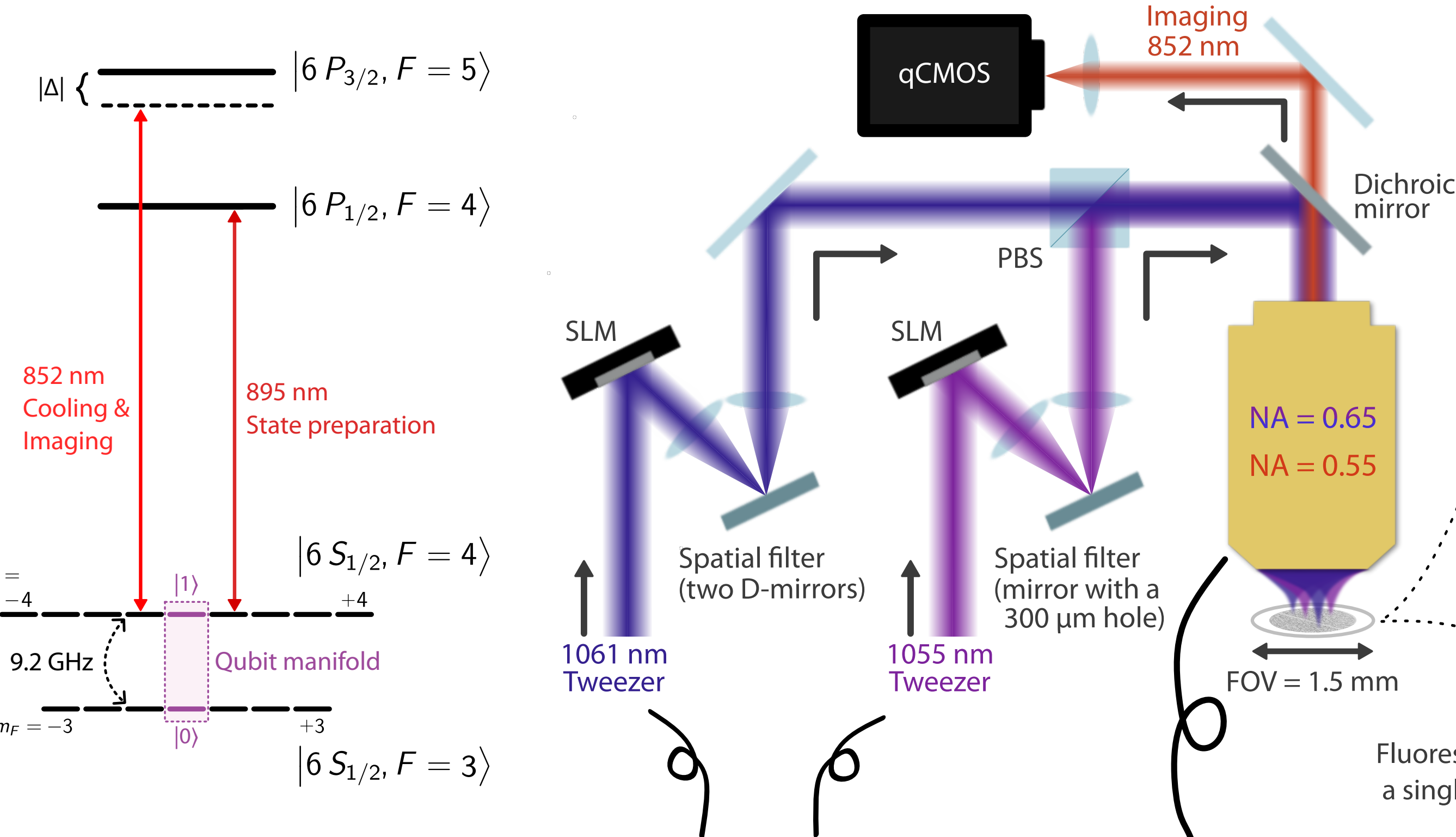
## 6,100 single <sup>133</sup>Cs atoms in 12,000 optical tweezers

Scaling up the fully programmable quantum system while preserving **low error rate** is crucial for quantum simulation, metrology, and computation. However, this still remains a **challenging problem** across all the platforms.

Here we demonstrate

- generation of **12,000 optical tweezers** using SLMs
- over 50% loading probability, trapping **6,100 single <sup>133</sup>Cs atoms** on average
- high imaging fidelity > **0.9999**
- high imaging survival > **0.99989**
- long vacuum-limited lifetime of **23 min**
- long coherence time of **T<sub>2</sub> = 12.6(1) s** with dynamical decoupling

1	1.008	1.00794	1	H	Hydrogen
2	4.0026	4.00260	2	He	Helium
3	6.94	6.941	3	Li	Lithium
4	9.0122	9.01218	4	Be	Beryllium
5	10.811	10.8107	5	B	Boron
6	12.011	12.0107	6	C	Carbon
7	14.003	14.00307	7	N	Nitrogen
8	15.999	15.99491	8	O	Oxygen
9	18.998	18.99840	9	F	Fluorine
10	20.015	20.01584	10	Ne	Neon
11	22.990	22.98977	11	Na	Sodium
12	24.304	24.30409	12	Mg	Magnesium
13	26.982	26.98154	13	Al	Aluminum
14	28.086	28.08583	14	Si	Silicon
15	29.96	29.96164	15	P	Phosphorus
16	30.974	30.97376	16	S	Sulfur
17	32.06	32.06199	17	Cl	Chlorine
18	35.45	35.453	18	Ar	Argon
19	39.098	39.0963	19	K	Potassium
20	39.962	39.96238	20	Ca	Calcium
21	44.956	44.95591	21	Sc	Scandium
22	47.88	47.88	22	Ti	Titanium
23	48.94	48.9404	23	V	Vanadium
24	50.942	50.9415	24	Cr	Chromium
25	51.996	51.9961	25	Mn	Manganese
26	54.938	54.93703	26	Fe	Iron
27	55.935	55.93494	27	Co	Cobalt
28	58.933	58.9332	28	Ni	Nickel
29	60.931	60.93103	29	Cu	Copper
30	62.93	62.93	30	Zn	Zinc
31	65.38	65.38	31	Ga	Gallium
32	67.925	67.9247	32	Ge	Germanium
33	69.723	69.7231	33	As	Arsenic
34	72.64	72.64	34	Se	Selenium
35	74.922	74.9216	35	Br	Bromine
36	76.924	76.9248	36	Kr	Krypton
37	79.904	79.904	37	Rb	Rubidium
38	81.905	81.9049	38	Sr	Strontium
39	84.913	84.9127	39	Y	Yttrium
40	86.909	86.9092	40	Zr	Zirconium
41	88.906	88.9062	41	Nb	Niobium
42	90.907	90.9073	42	Mo	Molybdenum
43	92.906	92.9063	43	Tc	Technetium
44	94.908	94.9078	44	Ru	Ruthenium
45	96.907	96.9069	45	Rh	Rhodium
46	98.906	98.9062	46	Pd	Palladium
47	100.906	100.9058	47	Ag	Silver
48	102.905	102.9055	48	Cd	Cadmium
49	104.904	104.9043	49	In	Indium
50	106.905	106.9057	50	Sn	Tin
51	108.906	108.9062	51	Pb	Lead
52	110.905	110.9051	52	Bi	Bismuth
53	112.905	112.9053	53	Po	Polonium
54	114.904	114.9041	54	At	Astatine
55	116.905	116.9053	55	Rn	Radon
56	118.905	118.9053	56	Fr	Francium
57	120.905	120.9053	57	Ra	Radium
58	122.905	122.9053	58	Ac	Actinium
59	124.905	124.9053	59	Th	Thorium
60	126.905	126.9053	60	Pa	Protactinium
61	128.905	128.9053	61	U	Uranium
62	130.905	130.9053	62	Np	Neptunium
63	132.905	132.9053	63	Pu	Plutonium
64	134.905	134.9053	64	Am	Americium
65	136.905	136.9053	65	Cm	Curium
66	138.905	138.9053	66	Bk	Berkelium
67	140.905	140.9053	67	Cf	Californium
68	142.905	142.9053	68	Es	Einsteinium
69	144.905	144.9053	69	Fm	Fermium
70	146.905	146.9053	70	Mn	Mendelevium
71	148.905	148.9053	71	Uu	Ununennium
72	150.905	150.9053	72	Uub	Unbibium
73	152.905	152.9053	73	Uuc	Untrium
74	154.905	154.9053	74	Uud	Unquadrium
75	156.905	156.9053	75	Uue	Unpentium
76	158.905	158.9053	76	Uuq	Unsextium
77	160.905	160.9053	77	Uur	Unseptium
78	162.905	162.9053	78	Uus	Unoctium
79	164.905	164.9053	79	Uut	Unnonium
80	166.905	166.9053	80	Uuq	Undecium
81	168.905	168.9053	81	Uuq	Undecium
82	170.905	170.9053	82	Uuq	Undecium
83	172.905	172.9053	83	Uuq	Undecium
84	174.905	174.9053	84	Uuq	Undecium
85	176.905	176.9053	85	Uuq	Undecium
86	178.905	178.9053	86	Uuq	Undecium
87	180.905	180.9053	87	Uuq	Undecium
88	182.905	182.9053	88	Uuq	Undecium
89	184.905	184.9053	89	Uuq	Undecium
90	186.905	186.9053	90	Uuq	Undecium
91	188.905	188.9053	91	Uuq	Undecium
92	190.905	190.9053	92	Uuq	Undecium
93	192.905	192.9053	93	Uuq	Undecium
94	194.905	194.9053	94	Uuq	Undecium
95	196.905	196.9053	95	Uuq	Undecium
96	198.905	198.9053	96	Uuq	Undecium
97	200.905	200.9053	97	Uuq	Undecium
98	202.905	202.9053	98	Uuq	Undecium
99	204.905	204.9053	99	Uuq	Undecium
100	206.905	206.9053	100	Uuq	Undecium



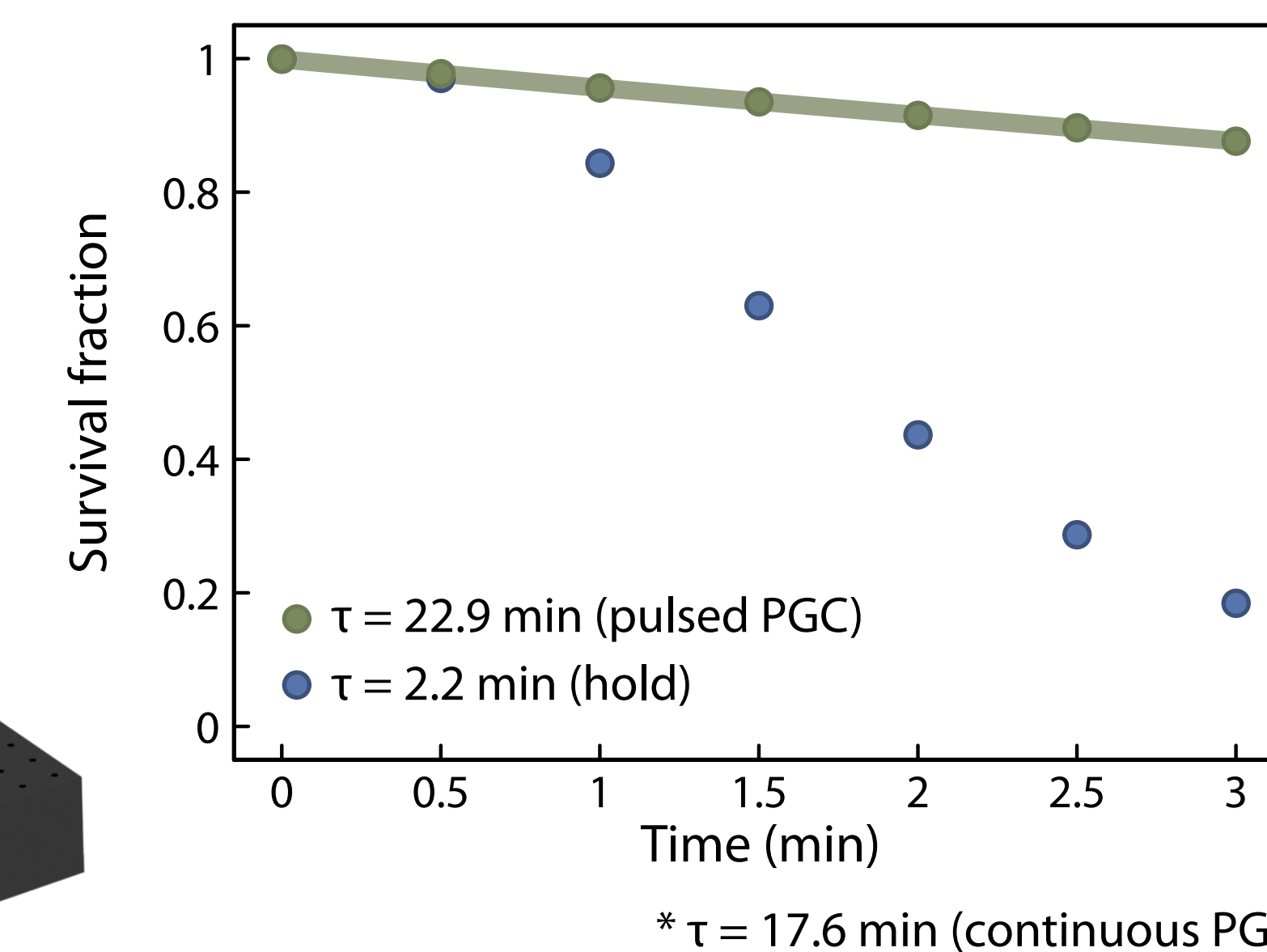
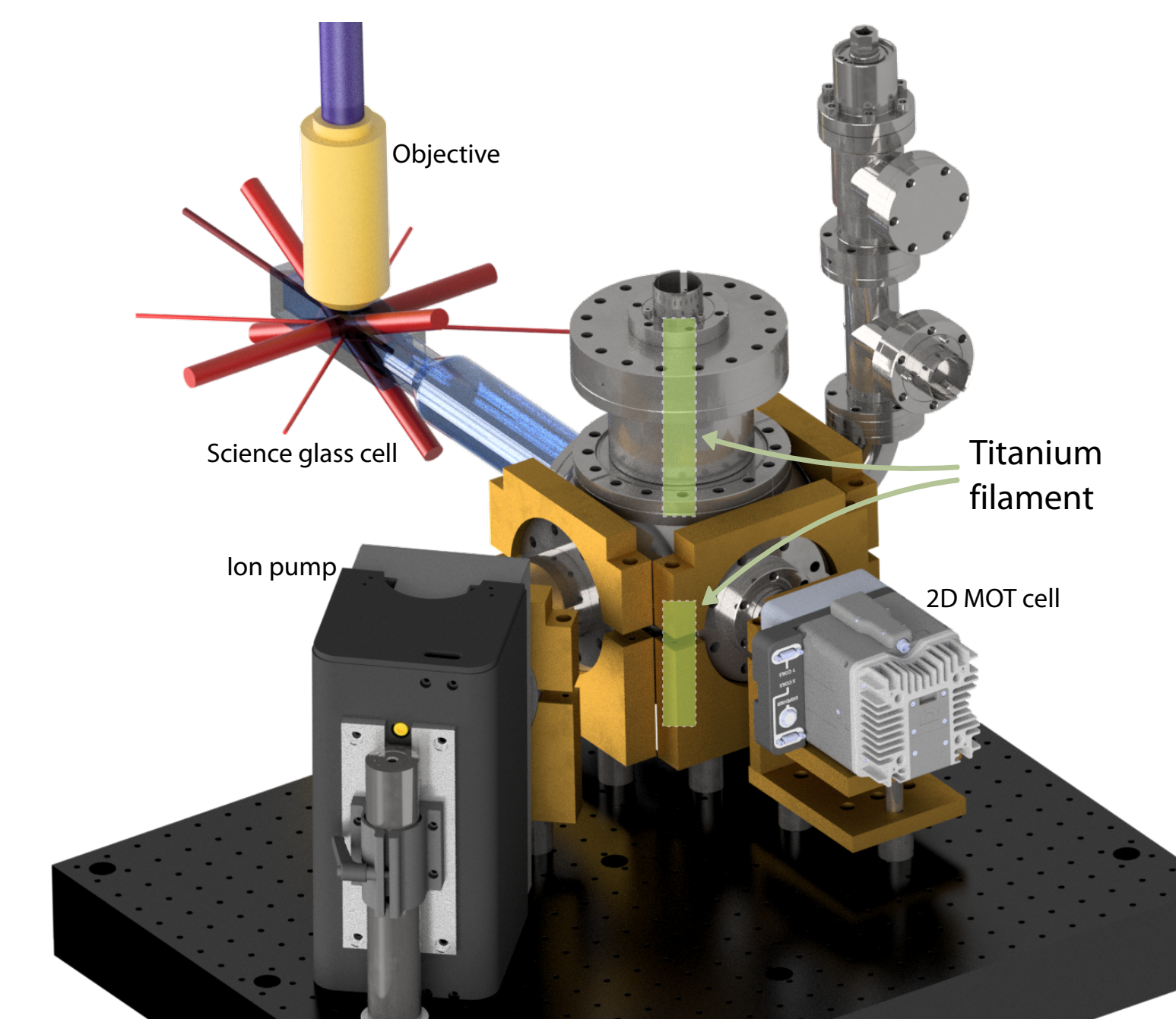
- 120 W output fiber-amplifier for each tweezer path. (Only around 8.5 W is currently used for 1055 nm path\*)
- \*1055 nm path makes only 4 rows of tweezers in the middle of the array

- Large numerical-aperture (NA)
- Large field-of-view (FOV)

- Current limitation**
- Aberration caused by the heating of the objective
  - Degradation of diffraction efficiency of the SLM

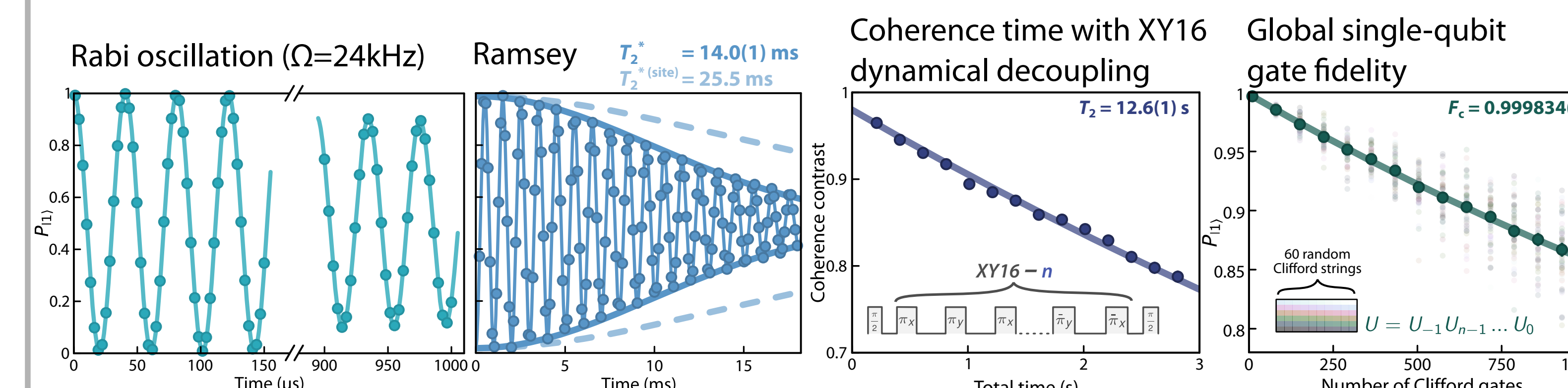
## Long vacuum-limited lifetime

- Long trapping time is essential for large-size tweezer arrays
- Vacuum-limited lifetime of around **23 min with a room-temperature apparatus**
- 10 ms polarization-gradient cooling is applied every 2 s
- **Titanium sublimation pump** coats wide range of surface of the vacuum parts



## Highly coherent hyperfine-qubits

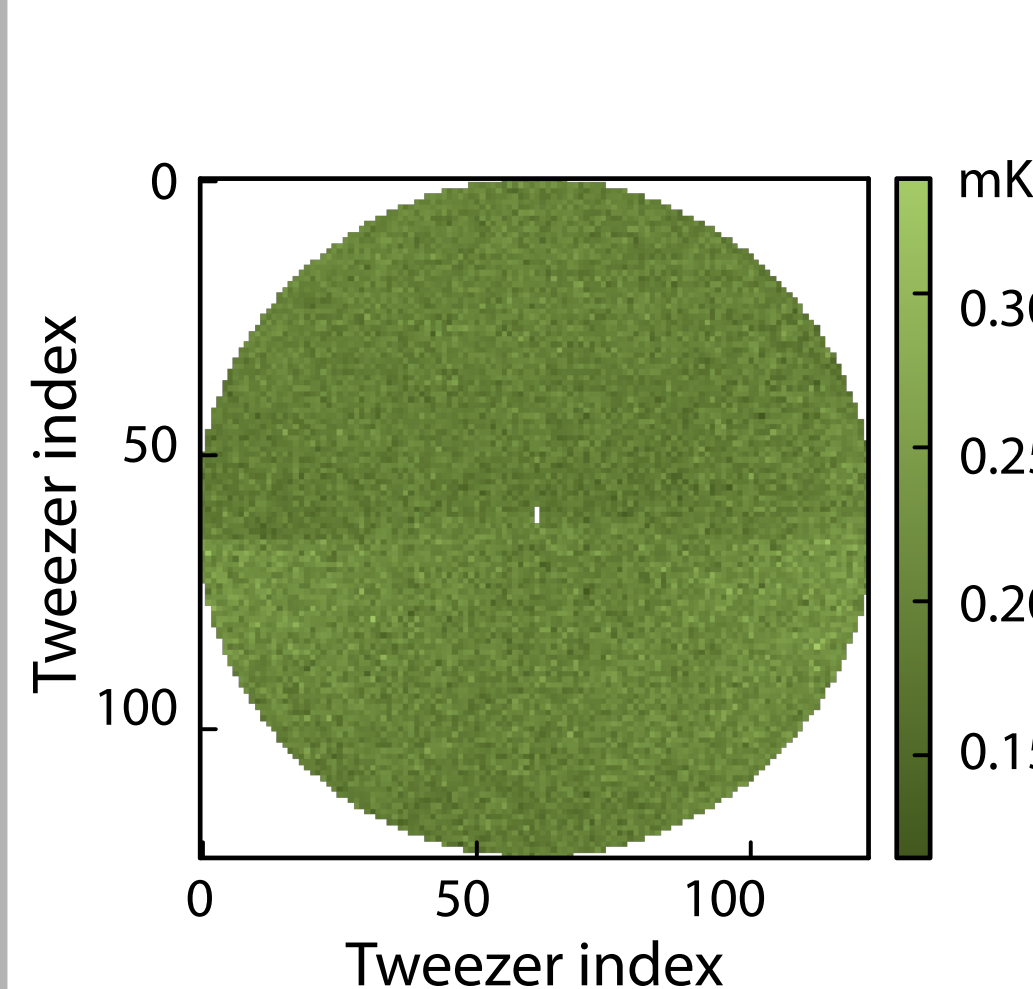
- Hyperfine-qubit ( $6 S_{1/2}$ ):  $|0\rangle \equiv |F=3, m_F=0\rangle$ ,  $|1\rangle \equiv |F=4, m_F=0\rangle$
- Global microwave single-qubit control
- $T_2^* = 14.0(1)$  ms and  $25.5$  ms for averaged and single-site, respectively
- $T_2 = 12.6(1)$  s with dynamical decoupling (XY16) sequence
- Long  $T_1$  time of  $T_1 = 119(1)$  s, enabled by the far-detuned wavelength of the tweezer light
- Global **single-qubit gate fidelity of > 0.9998** (Randomized benchmarking)



## Loading single atoms

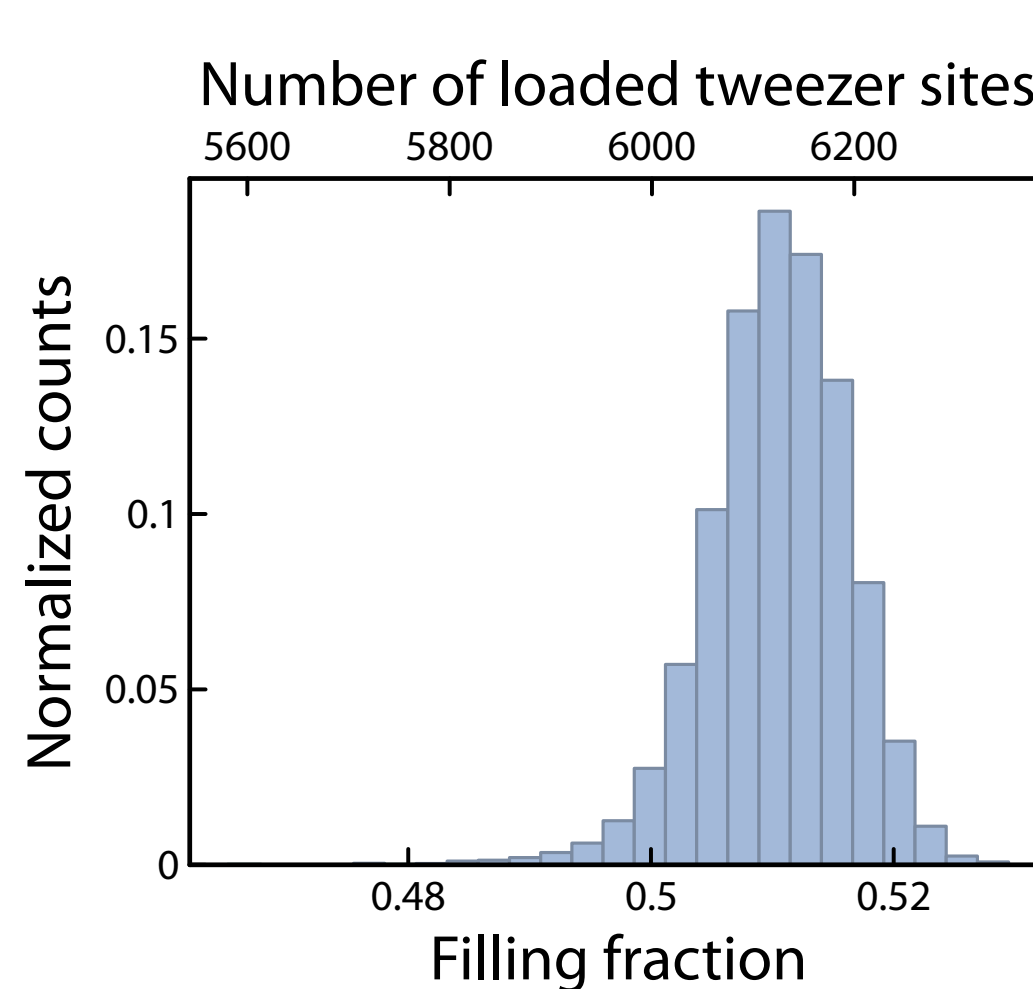
### Trap depth

- Trap depth of **0.2 mK** on ave
- Std of 11% across the array



### Filling fraction

- **6,100 atoms** load on ave
- Loading >50% on ave

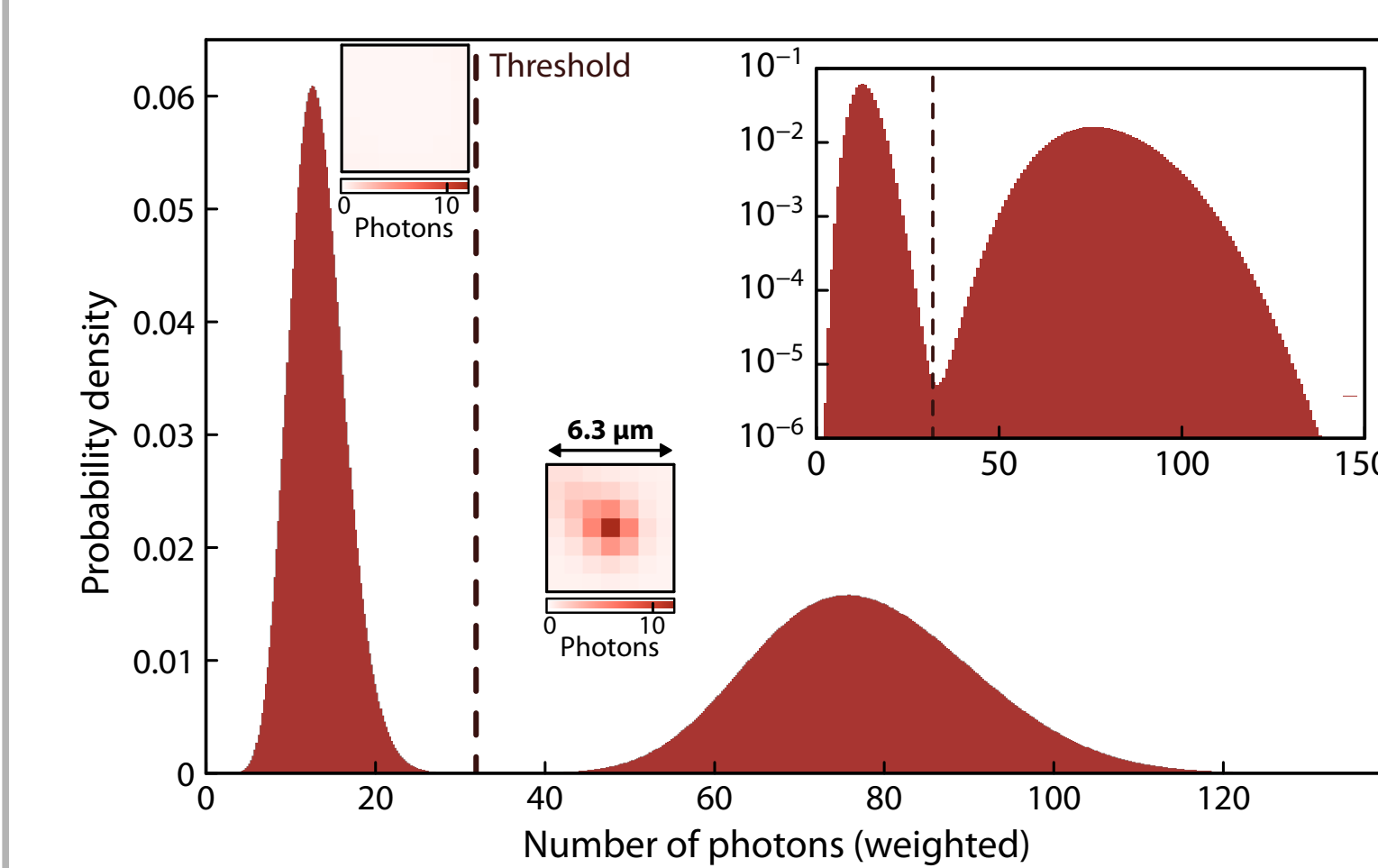


## High-fidelity imaging

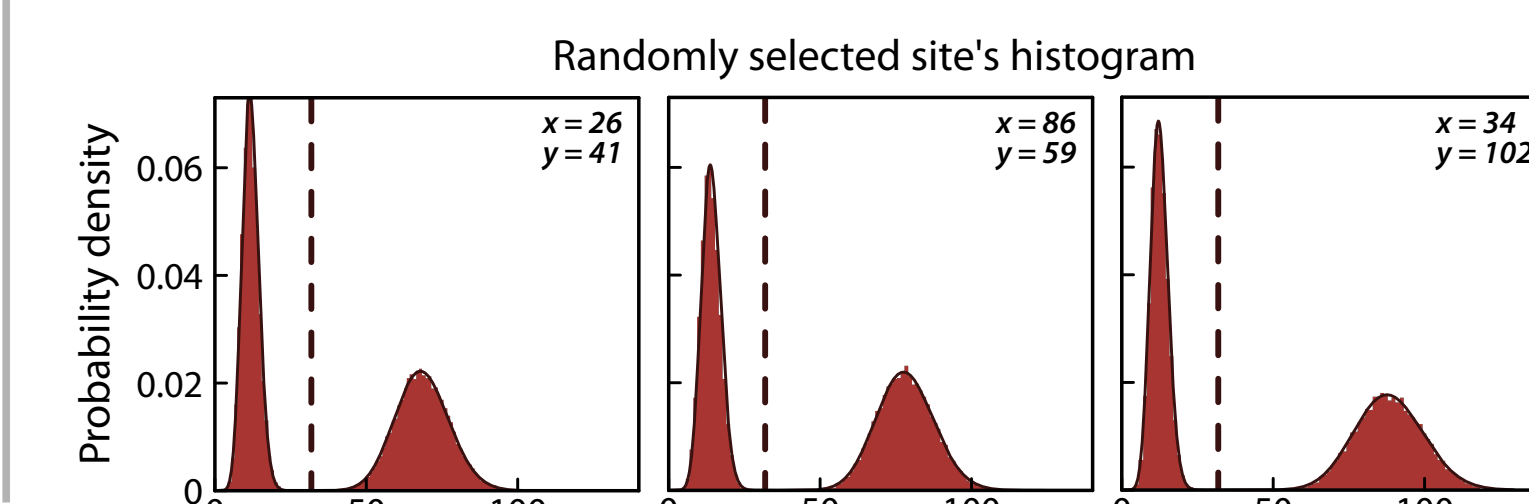
### Imaging fidelity (> 0.9999)

- 80 ms imaging at 852 nm (D2-transition)
- High-fidelity distinction between 0 / 1 atom
- Uniform scattering rate (around 12 % std)
- Photon collection efficiency of 2.7% (x QE)

### Site-averaged histogram



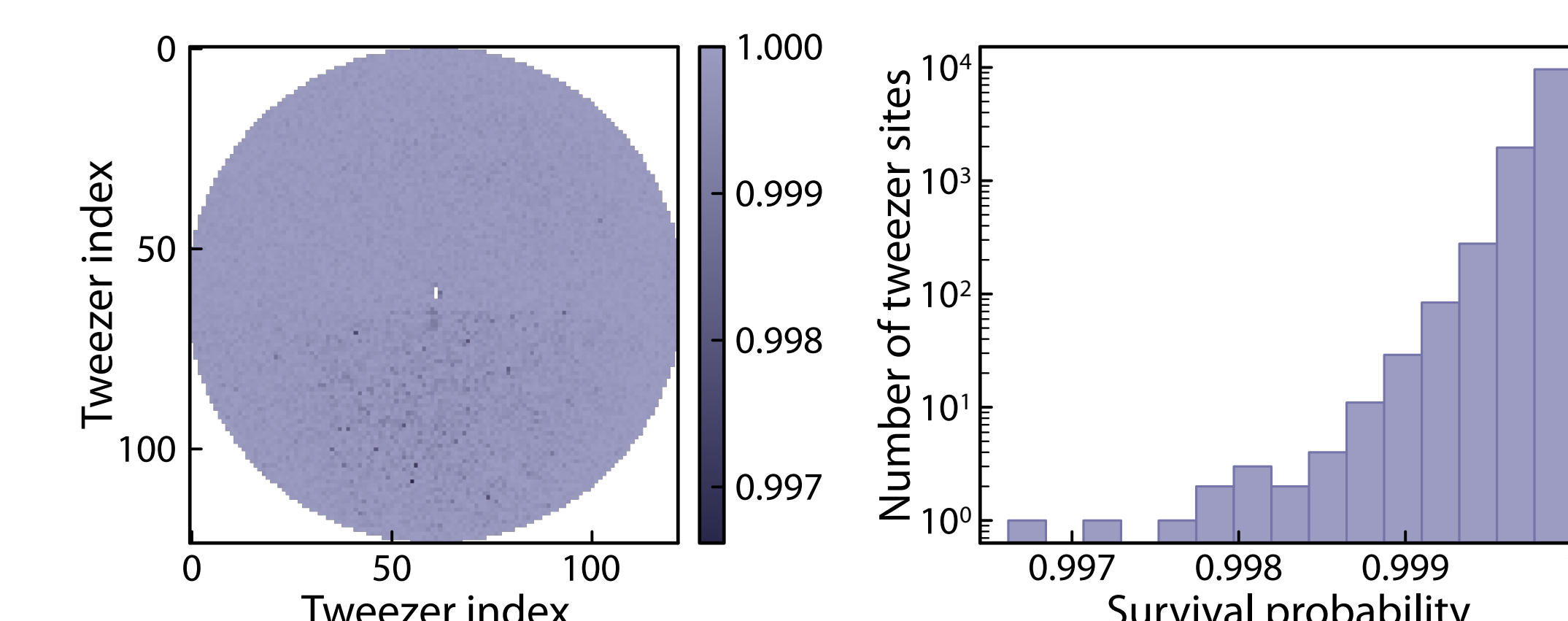
### Single-site histogram



### Imaging survival

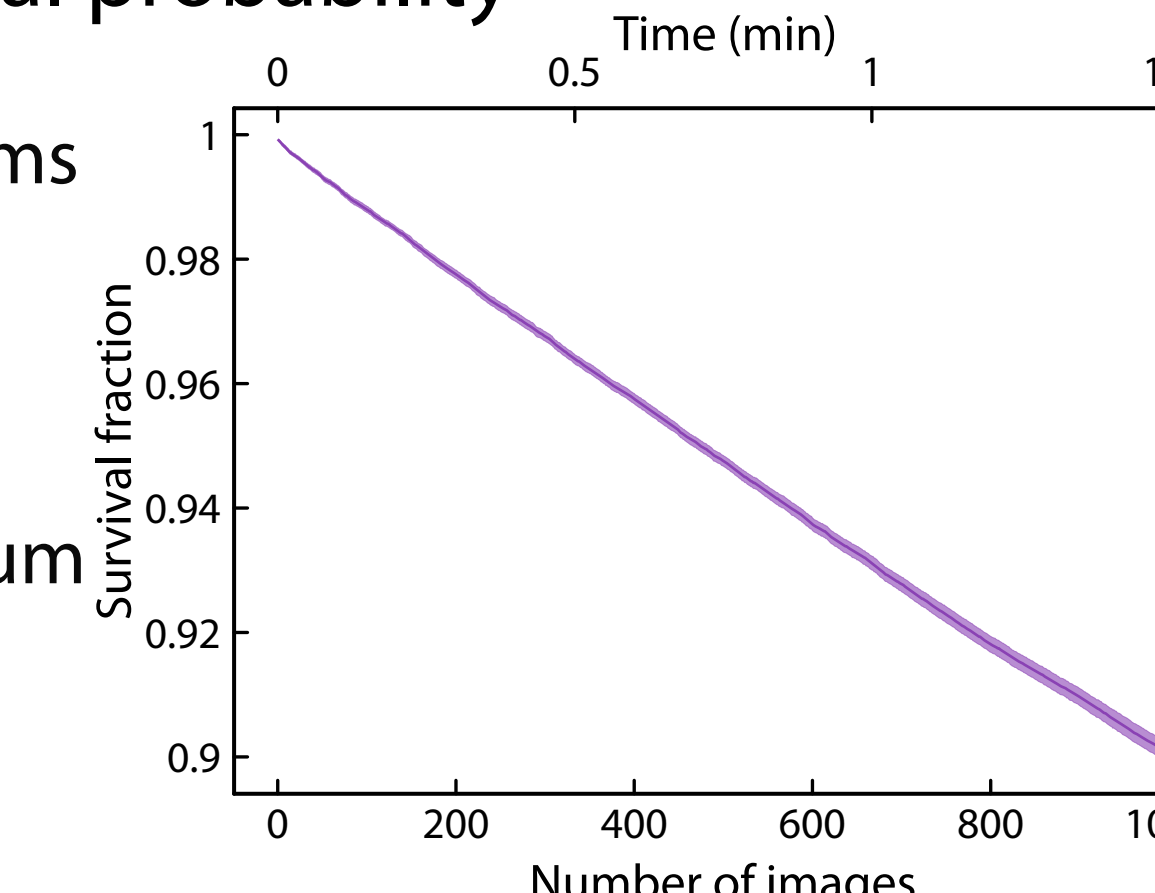
#### Single-shot imaging survival probability

- **99.98%** survival probability on average
- High survival probability across the whole array



#### Repeated-imaging survival probability

- **90%** of initially-loaded atoms survives after **1000 images**
- Steady-state survival prob of **0.99989**
- Mostly limited by the vacuum lifetime



## Outlook

### Rearrangement

- Rearrange quadrant by quadrant
- Switching quadrants with Galvo mirror
- Estimated rearrangement time of 100ms\*4

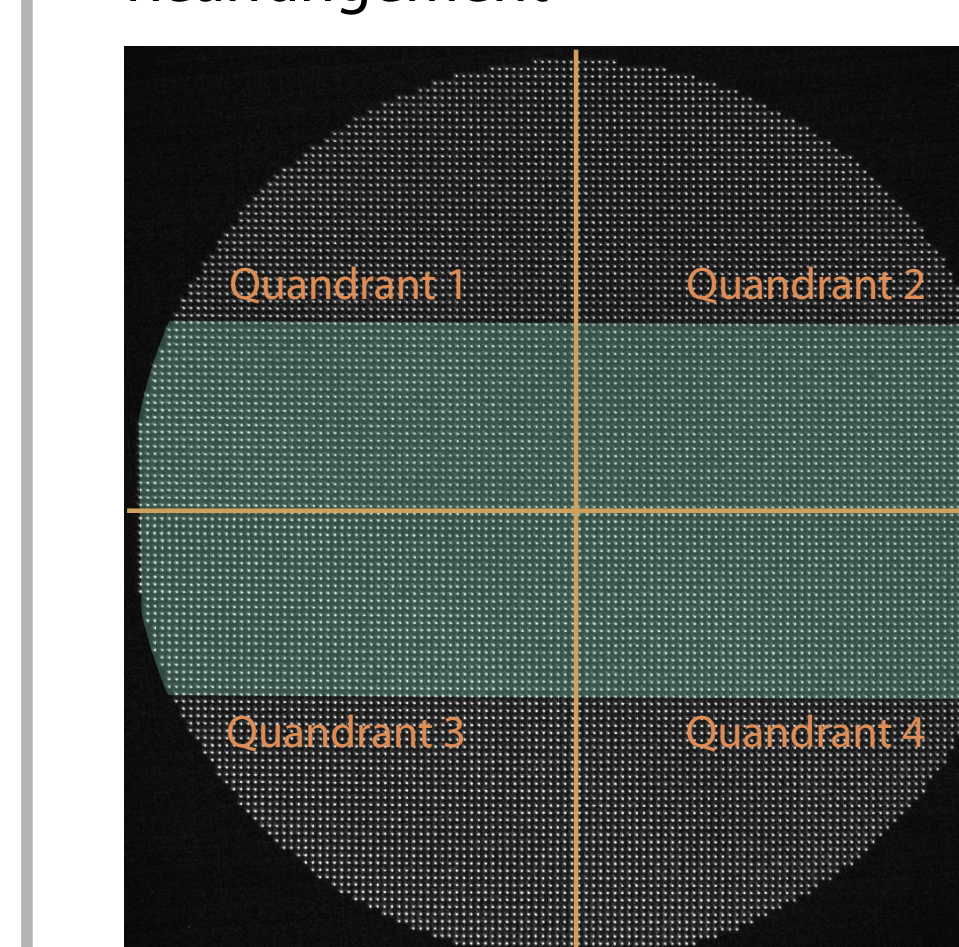
### Raman single-qubit control

- Fast single-qubit control (2 MHz)
- Local single-qubit control

### Rydberg interaction

- High power fiber-amplifier (120 W) @ 1061 nm
- Effective Rabi frequency of around 5 MHz
- 58  $S_{1/2}$  with 2.5 microm spacing (Noise-free model)
- CZ-gate fidelity of  $1-10^{-5}$  (time-optimal gate)
- Rydberg Bell state fidelity of  $1-10^{-4}$

### Rearrangement



### Zone-scheme architecture

