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Quantum Information Processing with Trapped Rydberg Ions

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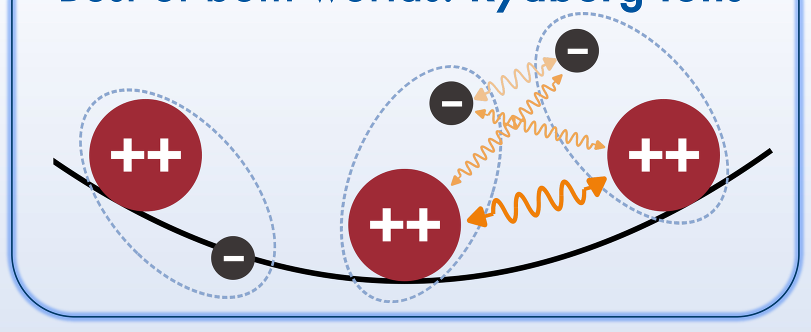
ABSTRACT

Combining the strong and long-range interaction of cold Rydberg atoms with the controllability of trapped ions, ultracold trapped Rydberg ions provide a promising platform for scalable quantum computing. We demonstrate how microwave-dressed Rydberg states result in rotating permanent dipole moments causing strong dipole-dipole interaction between ions in highly excited Rydberg states. Due to the large difference in time scales, the fast electronic dynamics of the Rydberg ions decouple from the slower oscillator modes in the linear Coulomb crystal. These properties allow us to realize a submicrosecond two-qubit gate between two Rydberg ions confined in a Paul trap reaching fidelities of > 99% under consideration of the finite lifetime of the Rydberg states at room temperature.

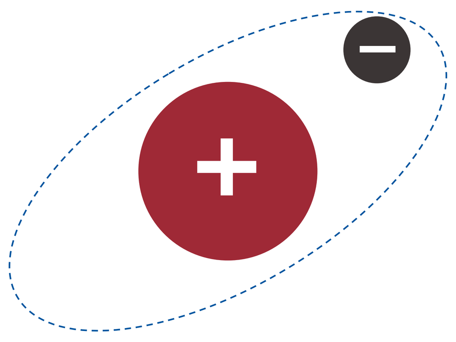
Rydberg atoms
Strong dipole-dipole interaction allows realization of fast gates

Best of both worlds: Rydberg Ions



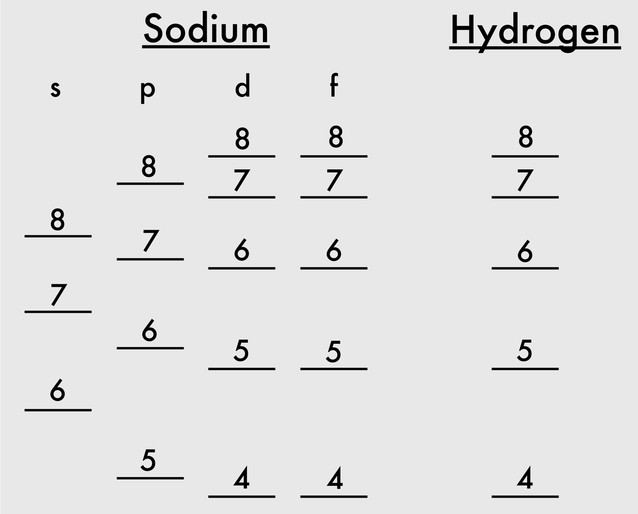
Trapped Ions
One of the best controlled and isolated quantum systems

RYDBERG PHYSICS

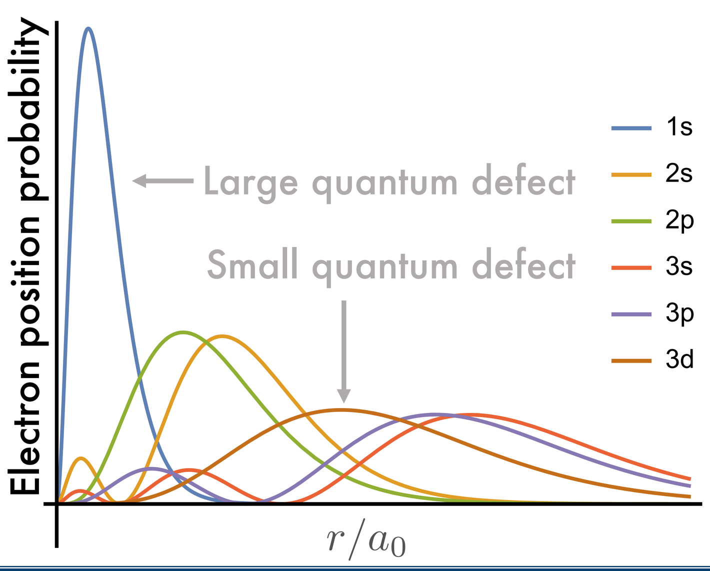


Binding Energy $E = -\frac{E_{\mathrm{Ryd}}}{(n-\delta_l)^2}$

Quantum defect



property	n-scaling	Z-scaling
energy levels E_n	n^{-2}	Z^2
level spacing ΔE_n	n^{-3}	Z^2
radius $\langle r \rangle$	n^2	Z^{-1}
dipole moment adjacent states d	n^2	Z^{-1}
polarizability α	n^7	Z^{-4}
radiative lifetime τ	n^3	Z^{-4}
dipole-dipole interaction C_3, $V_{dd} \sim R^{-3}$	n^4	Z^{-2}
van der Waals coefficient C_6, $V_{vdW} \sim R^{-6}$	n^{11}	Z^{-6}

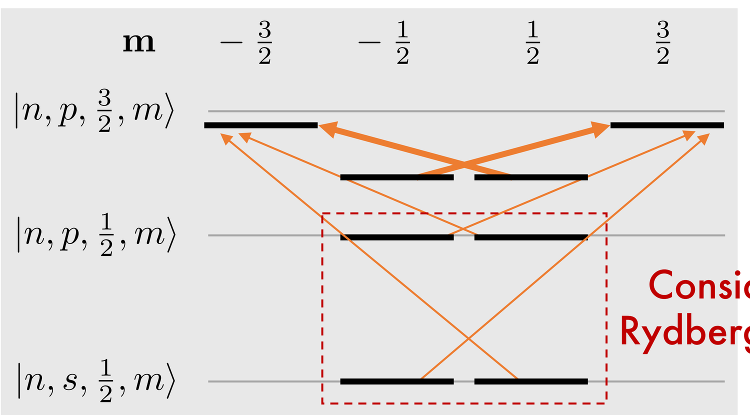


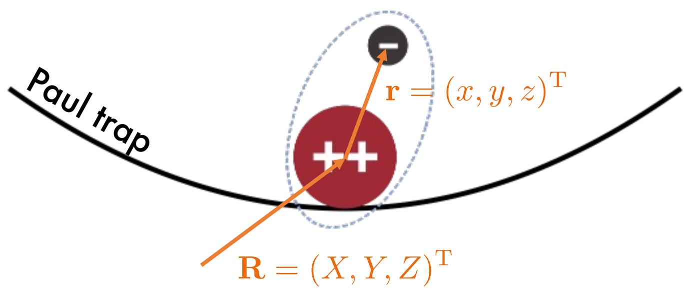
SINGLE TRAPPED RYDBERG IONS

Electronic Hamiltonian $H_{\mathrm{el}} = \frac{\mathbf{p}^2}{2m} + V(|\mathbf{r}|) + H_{\mathrm{FS}} + e\beta(x^2+y^2-2z^2) - e\alpha\cos(\omega t)(x^2-y^2) - e\mathbf{f}(t)\cdot\mathbf{r}$

electron; interaction with Paul trap; interaction with external fields

Fine structure splitting; Quadrupole shift; Coupling for $\Delta m = \pm 2$





MICROWAVE DRESSING

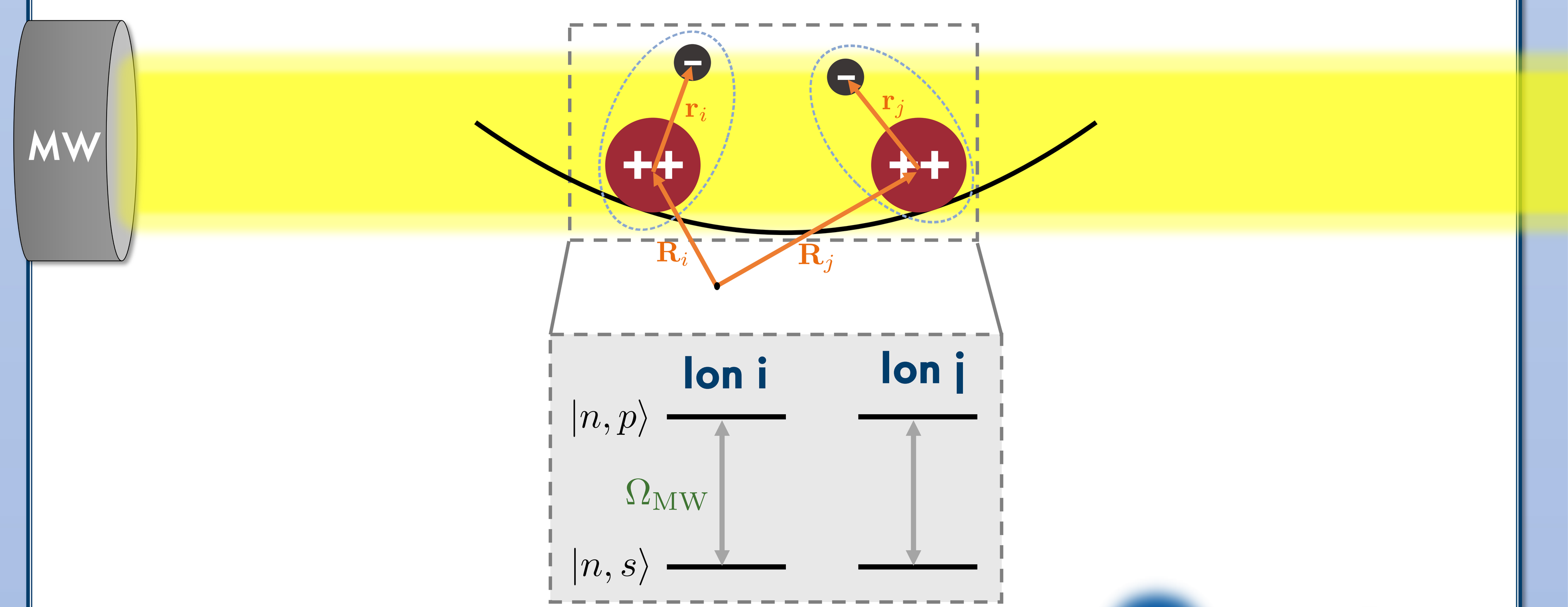
Dipole-dipole interaction $V_{\mathrm{dd}} = -\frac{1}{4\pi\epsilon_0}\frac{3(\mathbf{n}_{ij}\cdot\mathbf{d}_i)(\mathbf{n}_{ij}\cdot\mathbf{d}_j) - \mathbf{r}_i\cdot\mathbf{d}_j}{|\mathbf{R}_{ij}|^3}$

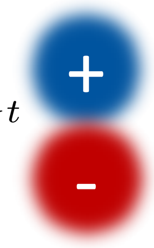
→No permanent dipole moments

→V_{dd} has no first order effect

→Second order: vdW $\sim n^{11}R^{-6}Z^{-6} \sim$ kHz

- Principle quantum number n is limited due to trap ionisation

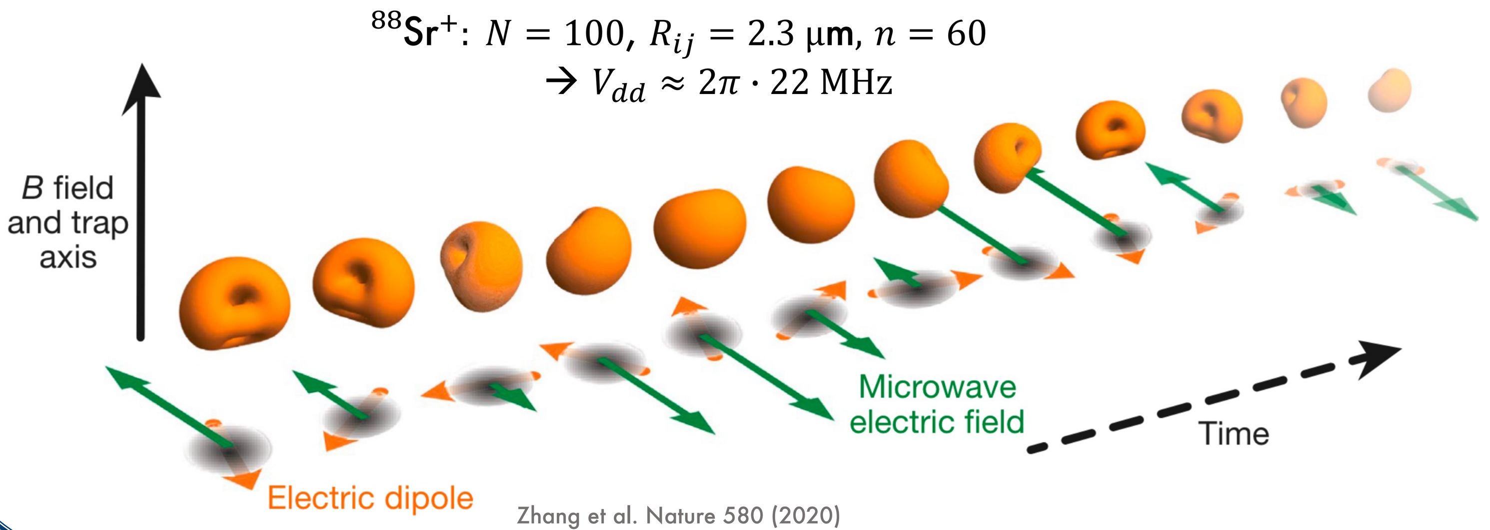


Dressed-states $|\pm\rangle \sim e^{-i\omega_{\mathrm{MW}}t}|n,p\rangle \mp |n,s\rangle \sim e^{-i\omega_{\mathrm{MW}}t}$  $\mp$ 

→ **Interacting rotating dipole moments**

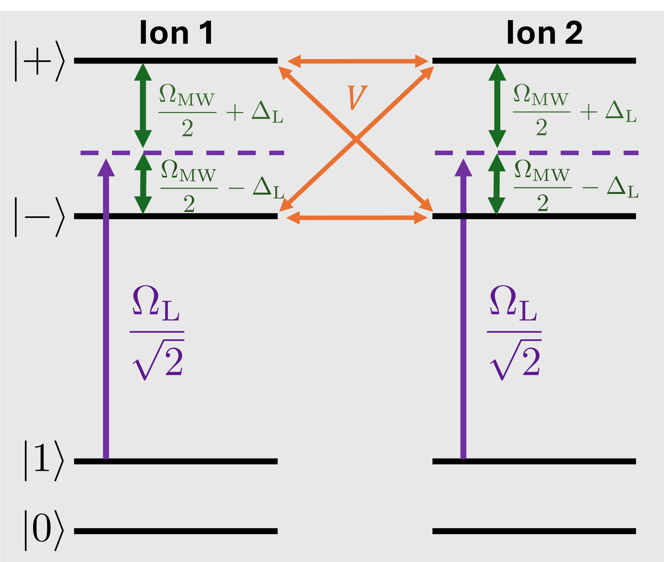
^{88}Sr$^+$: $N = 100$, $R_{ij} = 2.3$ µm, $n = 60$

→ $V_{dd} \approx 2\pi \cdot 22$ MHz



Zhang et al. Nature 580 (2020)

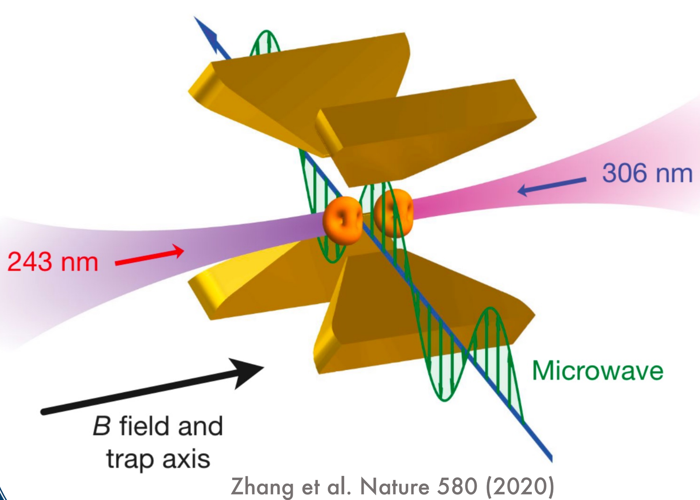
REALIZING FAST CZ-GATES



Hamiltonian:

$$H = \sum_{i=1}^{2}\Big[(\Delta_{\mathrm{L}} + \frac{\Omega_{\mathrm{MW}}}{2})|+\rangle\langle+|_i + (\Delta_{\mathrm{L}} - \frac{\Omega_{\mathrm{MW}}}{2})|-\rangle\langle-|_i + \frac{\Omega_{\mathrm{L}}}{2\sqrt{2}}\big(|+\rangle\langle 1|_i + |1\rangle\langle+|_i + |-\rangle\langle 1|_i + |1\rangle\langle-|_i\big)\Big]$$
$$+ \frac{V}{2}\Big[\big(|+\rangle\langle+|_1 - |-\rangle\langle-|_1\big)\big(|+\rangle\langle+|_2 - |-\rangle\langle-|_2\big) - \big(|+\rangle\langle-|_1 - |-\rangle\langle+|_1\big)\big(|+\rangle\langle-|_2 - |-\rangle\langle+|_2\big)\Big]$$

with the dressed states: $|\pm\rangle = \frac{1}{\sqrt{2}}(|n,p\rangle \mp |n,s\rangle)$



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Time-dependent pulse: $\Delta_{\mathrm{L}} = \Delta_{\mathrm{L}}(\mathbf{\Delta}_0, t)$, $\Omega_{\mathrm{L}} = \Omega_{\mathrm{L}}(\mathbf{\Omega}_0, t)$

$\Psi = \frac{1}{2}(|00\rangle + |01\rangle + |10\rangle + |11\rangle)$

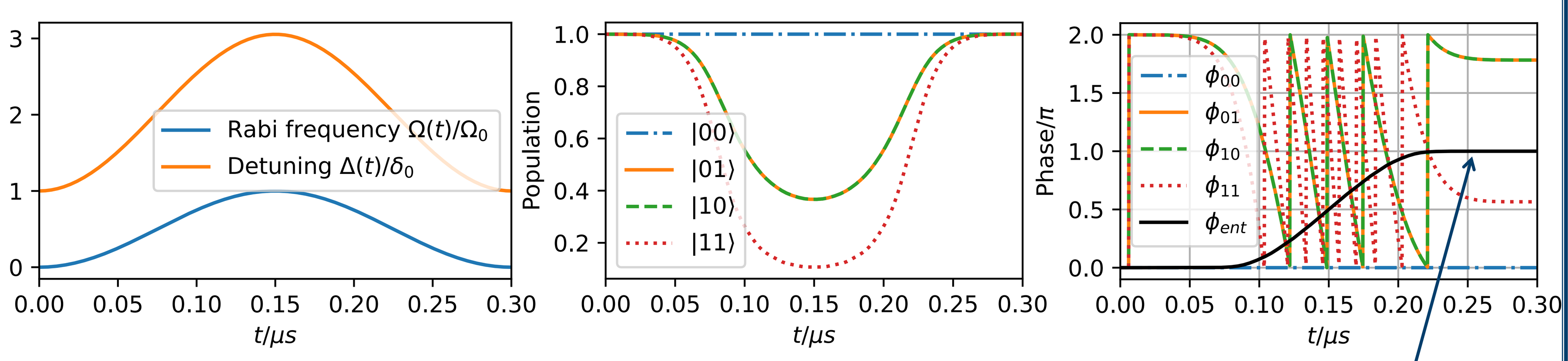
CZ — time-evolution $U(\tau, \Delta_0, \Omega_0)$

$\Psi_{\mathrm{B}} = \frac{1}{2}(|00\rangle + |01\rangle + |10\rangle - |11\rangle)$

Maximizing the fidelity $\mathcal{F}_{\mathrm{B}} = |\langle\Psi_{\mathrm{B}}|R^{(2)}_{\phi_{01}}R^{(1)}_{\phi_{10}}|\Psi(\tau)\rangle|^2$ yields the optimal pulse parameters

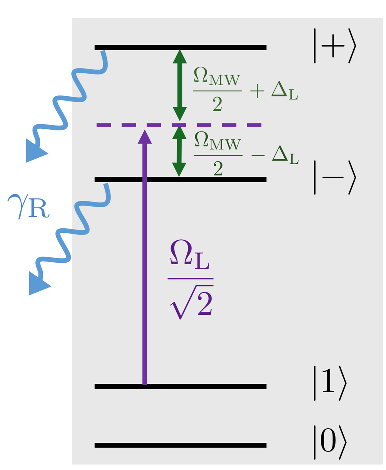
Resulting CZ-gate without noise $\Omega_{\mathrm{L}}(t) = \Omega_0\sin^2\left(\frac{\pi t}{\tau}\right)$, $\Delta_{\mathrm{L}}(t) = \delta_0 - \Delta_0\sin^2\left(\frac{\pi t}{\tau}\right)$

Three optimization parameters



$\phi_{\mathrm{ent}} = \phi_{11} - 2\phi_{10}$

Fidelity loss due to finite lifetime of Rydberg states

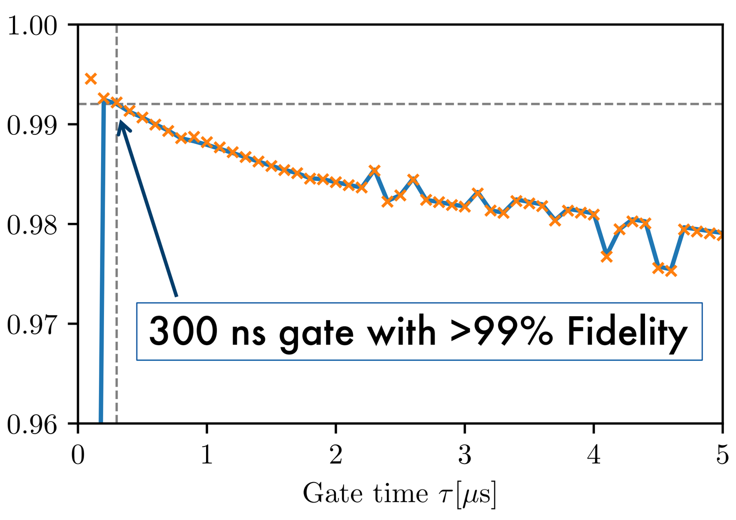


Approximation via non-Hermitian Hamiltonian (solid line)

$H_{\mathrm{R}} \approx -i\frac{\gamma_{\mathrm{R}}}{2}\sum_{i=1}^{2}[|+\rangle\langle+|_i + |-\rangle\langle-|_i]$

Fidelity loss approximation (markers)

$\mathcal{F}_{\mathrm{B}} \approx \left|1 - \frac{\gamma_{\mathrm{R}}}{8}\int_0^{\tau}\mathrm{d}t\sum_{i=1}^{2}[p_+^{(i)} + p_-^{(i)}]\right|^2$



OUTLOOK

Implementation of multi-ion gates, e.g., native CCZ-gate → Development of quantum error correction protocols → Design of scalable and fault-tolerant architectures for quantum information processing

Müller, M. et al. P. New J. Phys. 10, 093009 (2008).
Zhang, C. et al. Nature 580, 345–349 (2020).
Mokhberi, A. et al. Academic Press 69, 233–306 (2020).