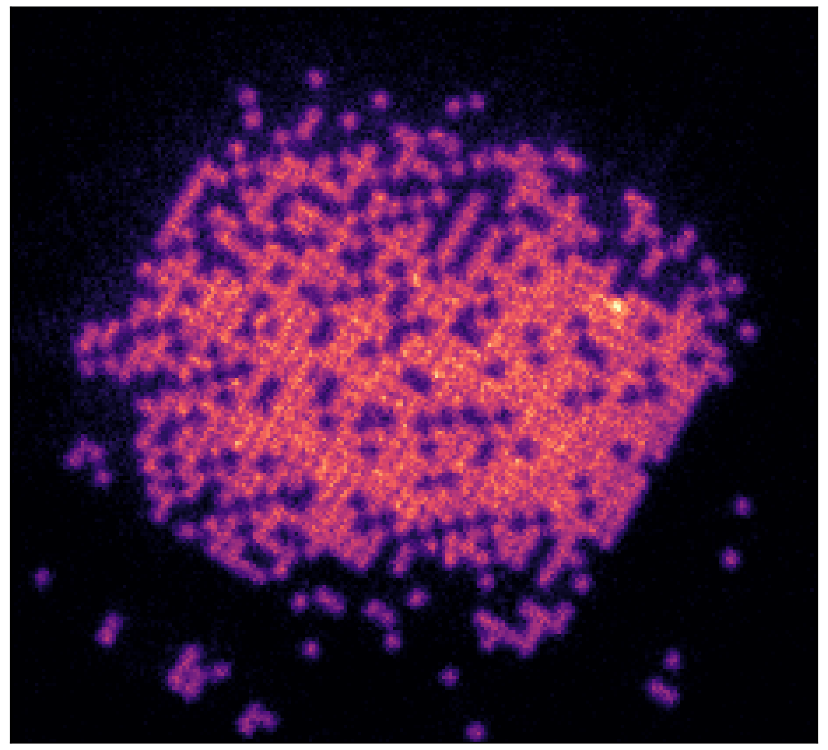
Quantum simulation of U(1) lattice gauge theories with neutral atoms in optical lattices

Monika Aidelsburger
Max-Planck Institut für Quantenoptik
Ludwig-Maximilians Universität München
Munich Center for Quantum Science & Technology

www.mpq.mpg.de/eng-quantum-systems



GEFÖRDERT VOM
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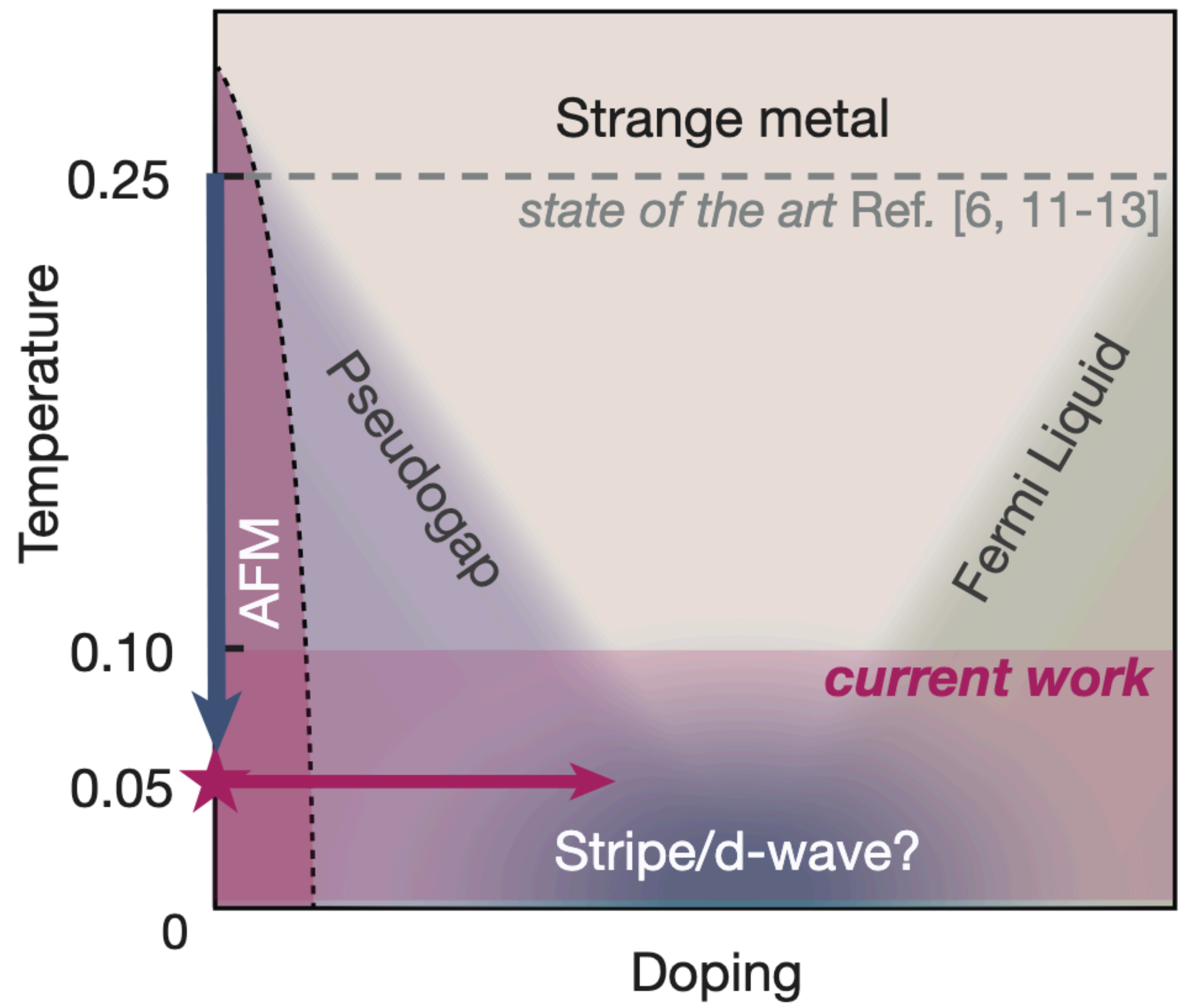
Deutsche Forschungsgemeinschaft
European Research Council
Funded by the European Union

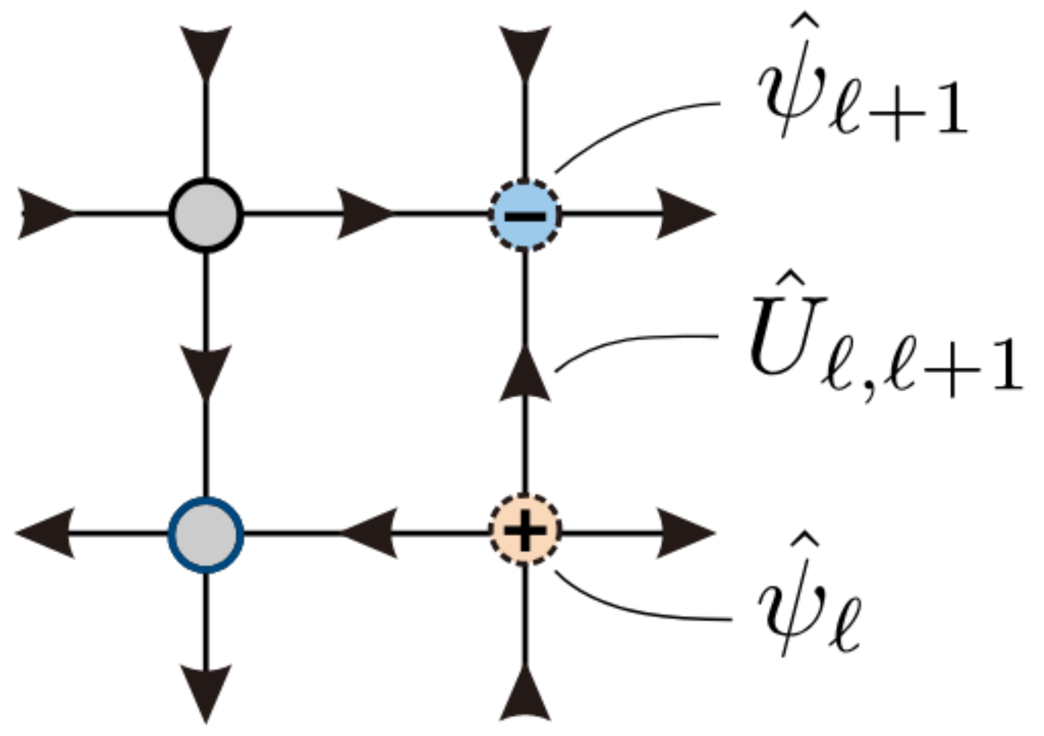
Quantum simulation with neutral atoms in optical lattices

Doped Fermi-Hubbard



Xu,...,Greiner, arXiv:2502.00095
Bohrdt *et al.*, Annals of Physics (2021)

Lattice gauge theories

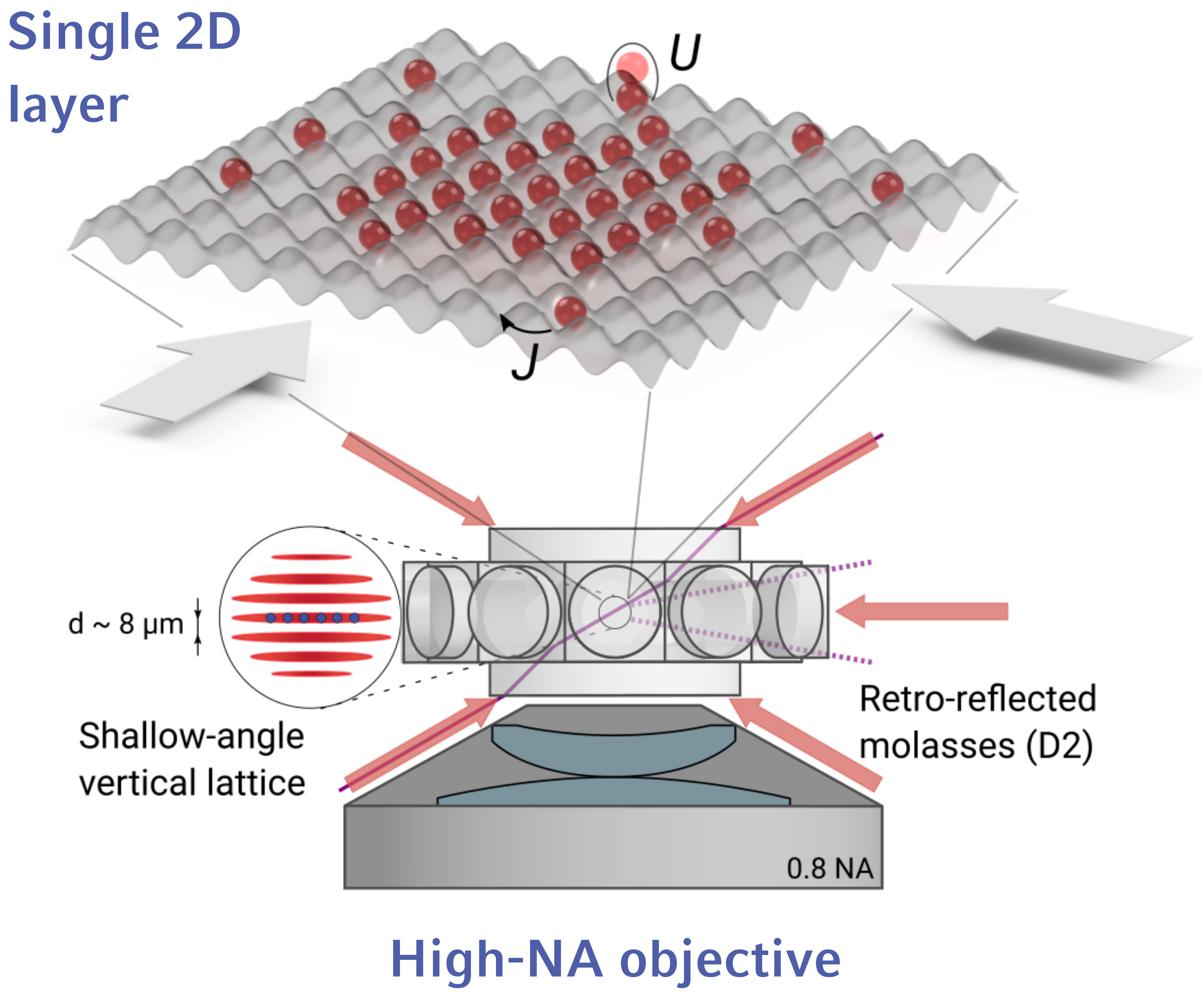


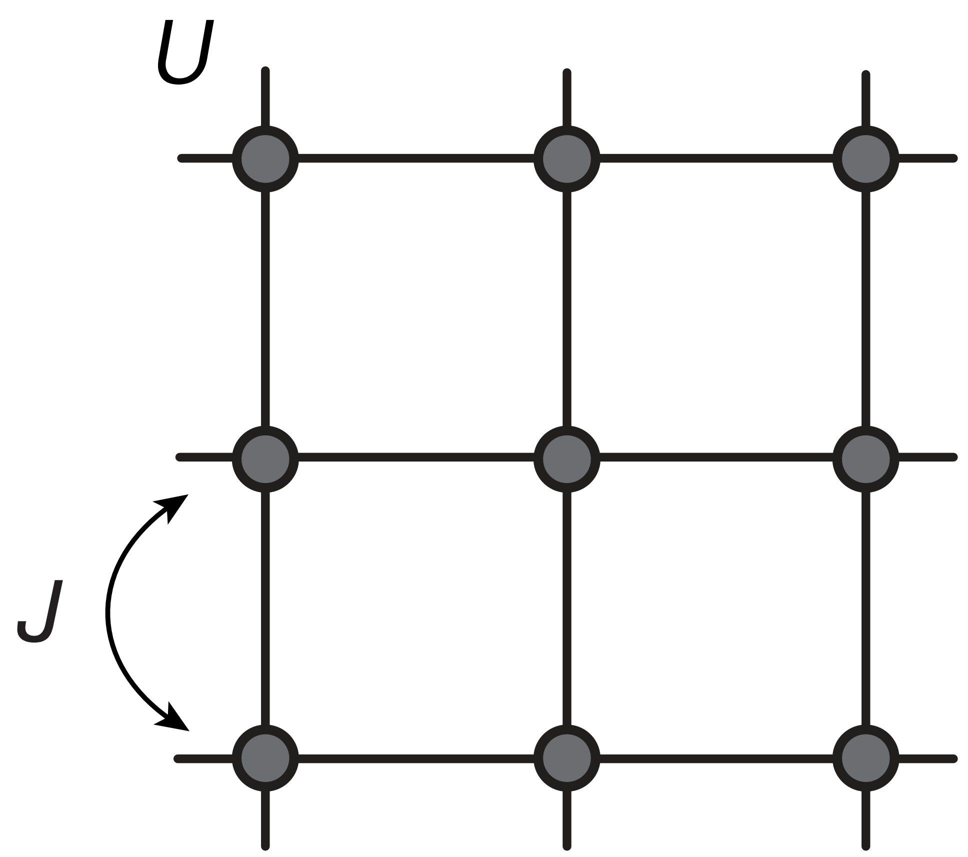
Yang,...,Pan, Nature (2020)
Halimeh,..., Aidelsburger, Nature Physics (2025)

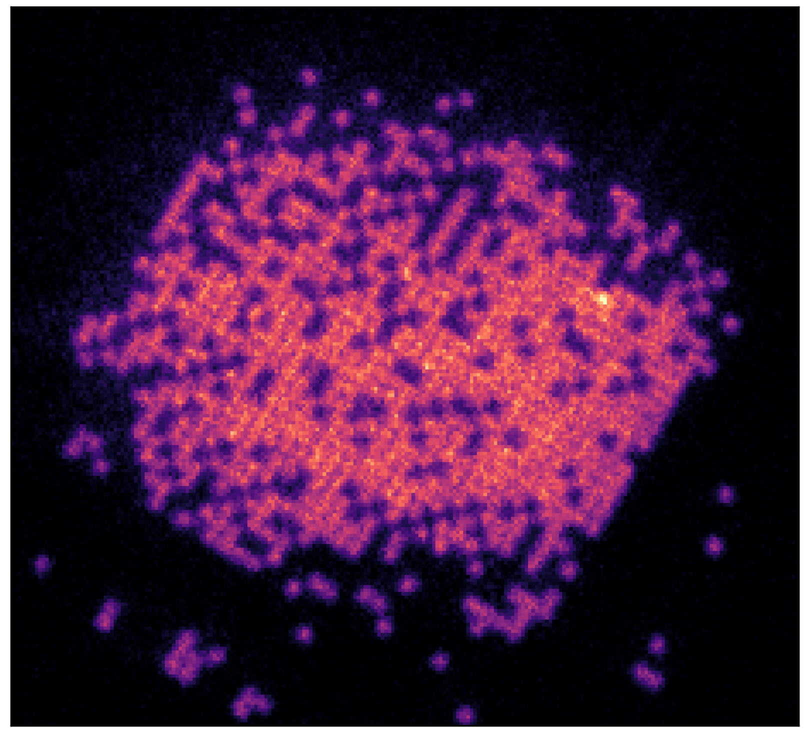
Direct implementation of Hamiltonian

Stability to errors & quantum advantage: Rahul Trivedi, Adrian Franco Rubio, Ignacio J. Cirac, Nature Commun. 15, 6507 (2024)

Quantum simulation of Hubbard models





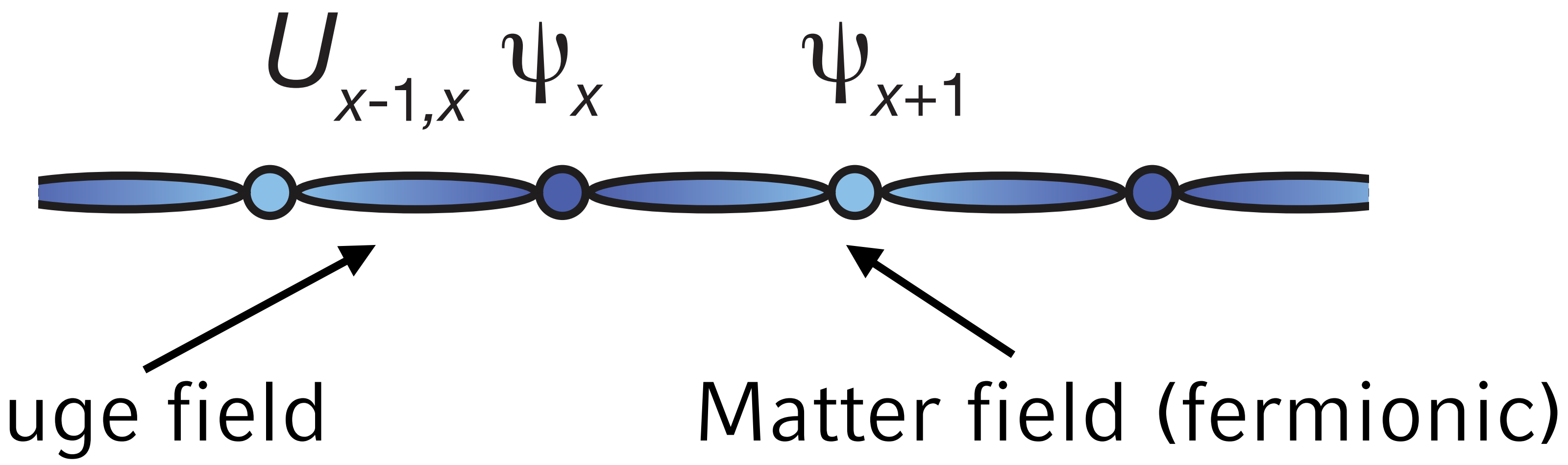

Cs atoms

$$\hat{H} = -J \sum_{\langle i,j \rangle} \hat{a}_i^\dagger \hat{a}_j + \frac{U}{2} \sum_i \hat{n}_i(\hat{n}_i - 1)$$

I. Bloch et al. Rev. Mod. Phys. 80, 885 (2008); C. Gross and I. Bloch, Science 357 (2017)

Gauge theories

Lattice gauge theories:



K. G. Wilson

Challenges for Quantum simulation:

- Implement matter and gauge fields
- Realize local symmetries (Gauss's law)

$$\boxed{\nabla \cdot \mathbf{E} = \frac{\rho}{\epsilon_0}}$$

U.-J. Wiese *et al.* Ann. Phys. **525**, 777-796 (2013); E. Zohar *et al.* Rep. Prog. Phys. **79**, 014401 (2015);
M. Dalmonte *et al.* Contemp. Phys. **57**, 388-412 (2016); M. Banuls *et al.* Eur. Phys. J. D **74**, 165 (2020)

U(1) lattice gauge theory in 1D

Quantum electrodynamics in 1D

lattice Schwinger model

gauge-invariant matter-gauge coupling

$$H_{\mathrm{LGT}} = -w \sum_j \left(\psi_j^\dagger U_{j,j+1} \psi_{j+1} + \mathrm{h.c.} \right)$$

$$+ m \sum_j (-1)^j \psi_j^\dagger \psi_j + g \sum_j E_{j,j+1}^2$$

w : nearest-neighbor tunneling

m : mass of "positrons" and "electrons"

$E_{j,j+1}$: electric field operator

$$[E_{i,i+1}, U_{j,j+1}] = \delta_{i,j} U_{j,j+1}$$

Kogut & Susskind, PRD 11, 395 (1975)
Chandrasekharan & Wiese, Nucl. Phys. B 492, 455 (1997)

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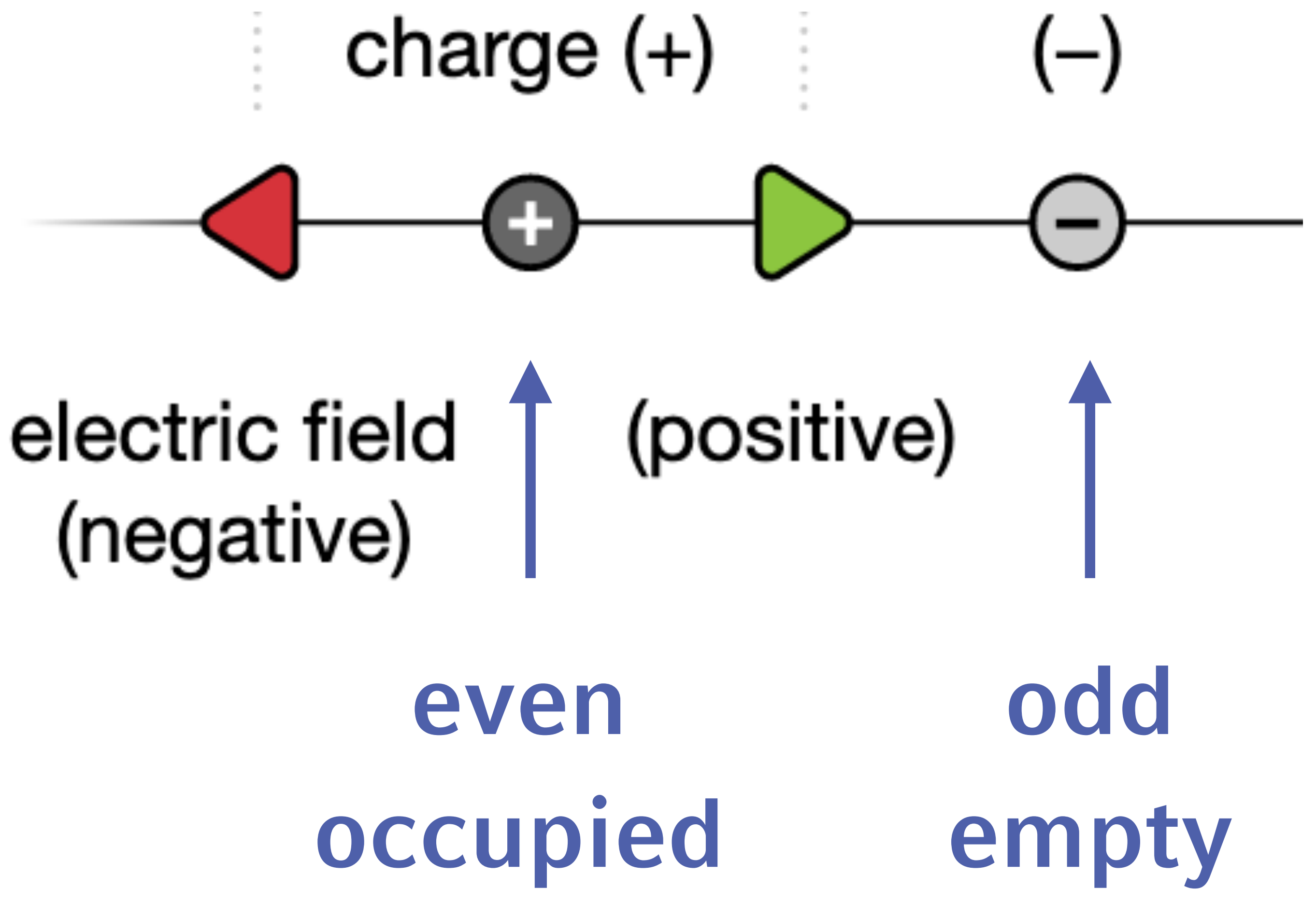
Local charge:

$$\boxed{q_j = \psi_j^\dagger \psi_j - \frac{1-(-1)^j}{2}}$$



Kogut & Susskind, PRD 11, 395 (1975)
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Gauss's law:

$$\boxed{G_j = E_{j,j+1} - E_{j-1,j} - q_j}$$

Physical states: $G_j |\Psi\rangle = 0$

Kogut & Susskind, PRD 11, 395 (1975)
Chandrasekharan & Wiese, Nucl. Phys. B 492, 455 (1997)

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Spin-1/2 quantum link model (QLM):

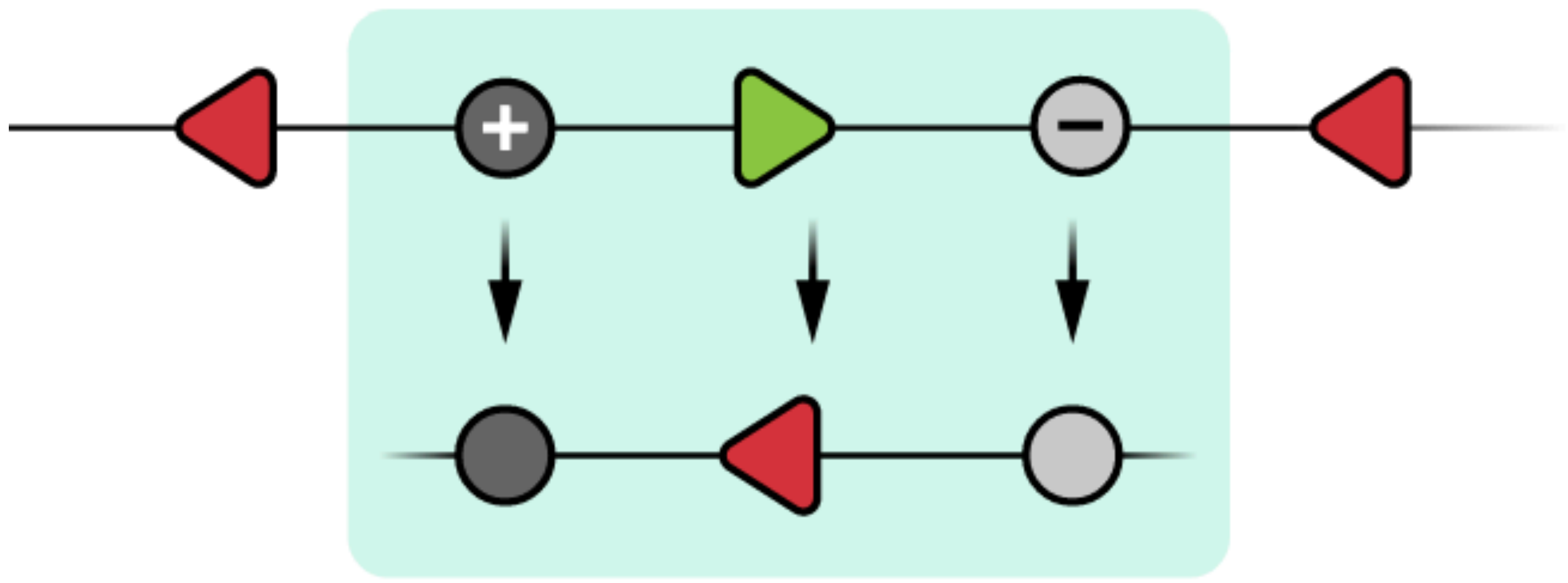
$$\boxed{\begin{aligned} E_{j,j+1} &\to S^z \\ U_{j,j+1} &\to S^+ \end{aligned}}$$

reduced Hilbert-space for link operators

Kogut & Susskind, PRD 11, 395 (1975)
Chandrasekharan & Wiese, Nucl. Phys. B 492, 455 (1997)

U(1) lattice gauge theory in 1D

Basic dynamics:



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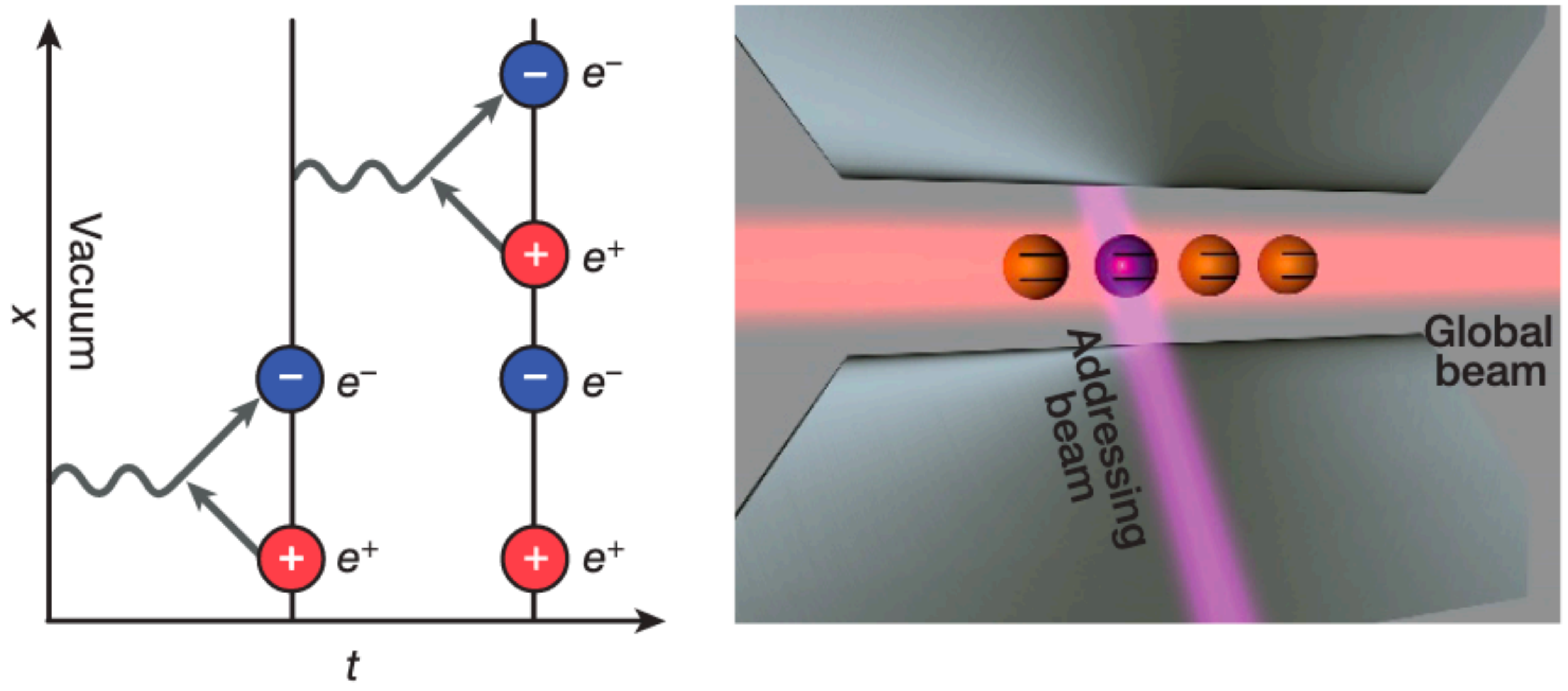
Chandrasekharan & Wiese, Nucl. Phys. B 492, 455 (1997)

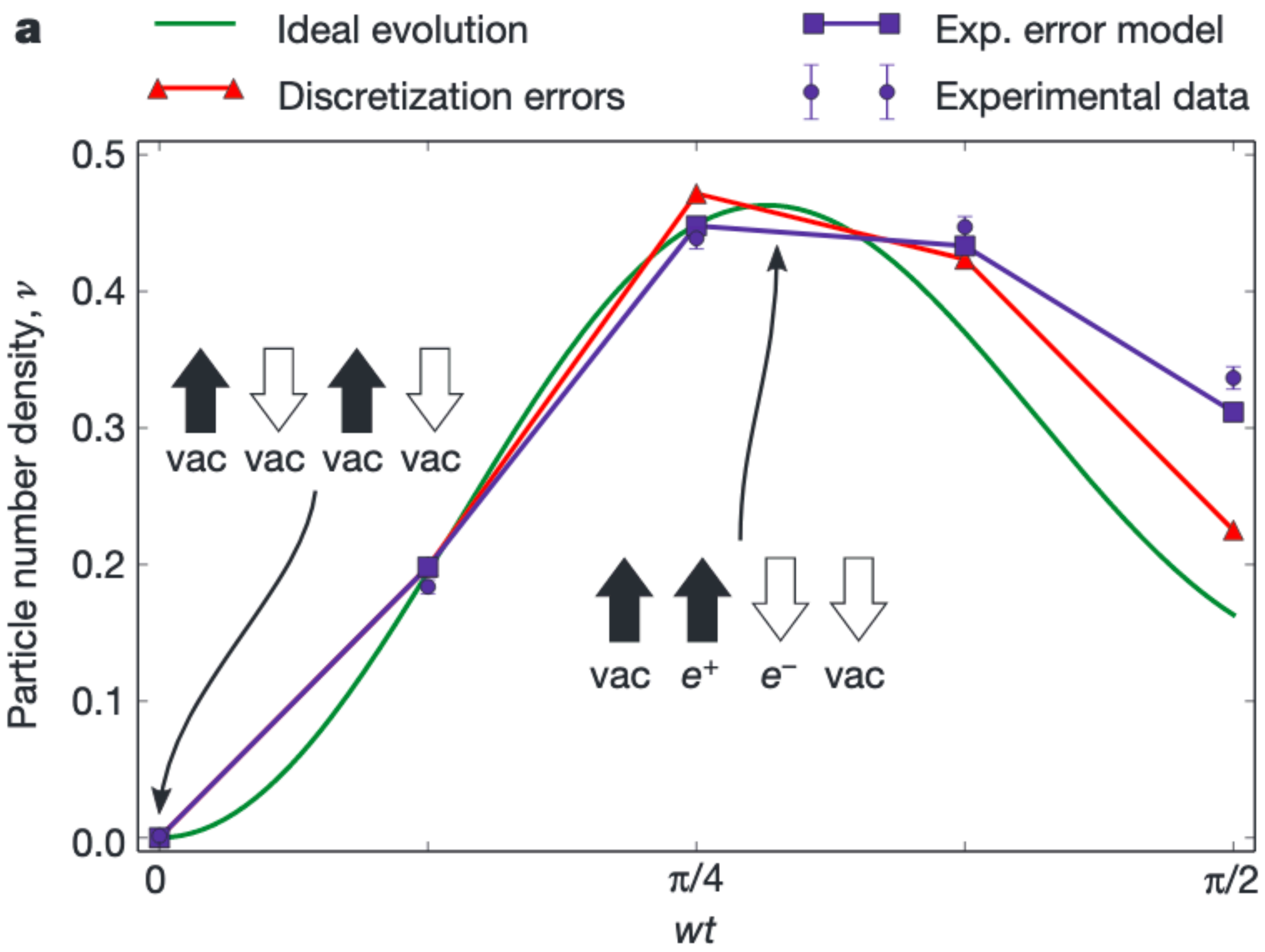
State-of-the-art

Few-ion quantum simulation

particle-antiparticle creation processes



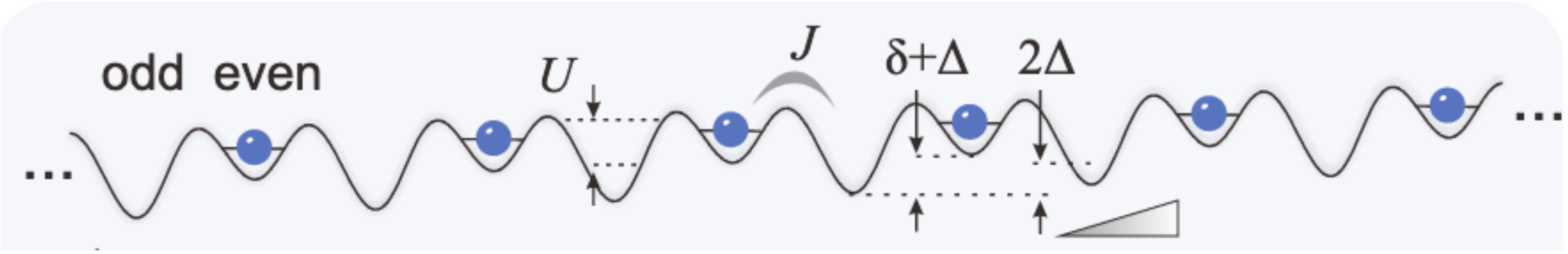
E. A. Martinez *et al.* Nature **534**, 516-519 (2016);
N. H. Nguyen et al. PRX Quantum **3**, 020324 (2022)



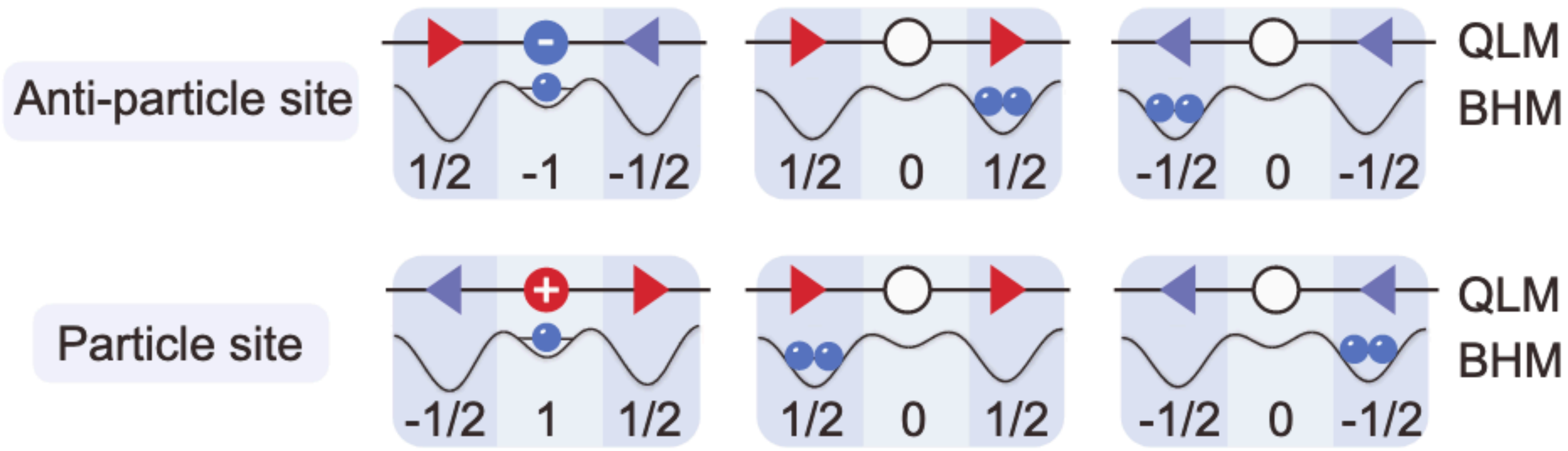
Gauge-fields are eliminated ↔ exotic long-range interactions

Cold bosonic atoms in tilted superlattices

Spin-1/2 quantum link model: staggered 1D Bose-Hubbard chains



$$\delta \gg J$$
$$U \approx 2\delta$$



Energy penalties suppress unwanted processes
→ constrained dynamics
→ gauge-invariant coupling

$|0\rangle, |1\rangle$ $|0\rangle, |2\rangle$

$$\hat{\psi}_\ell \hat{S}^+_{\ell,\ell+1} \hat{\psi}_{\ell+1} \simeq \hat{b}_{2\ell} (\hat{b}^\dagger_{2\ell+1})^2 \hat{b}_{2\ell+2} / \sqrt{2}$$

B. Yang et al. Nature **587**, 392-396 (2020)

Cold bosonic atoms in tilted superlattices

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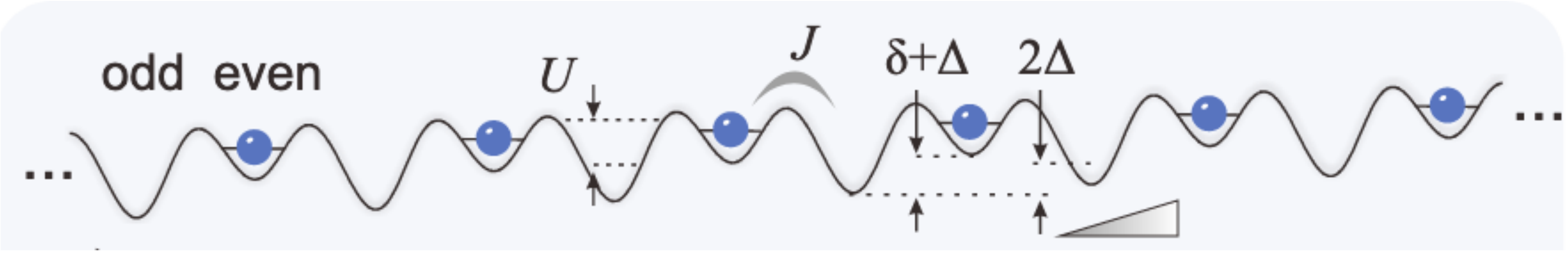
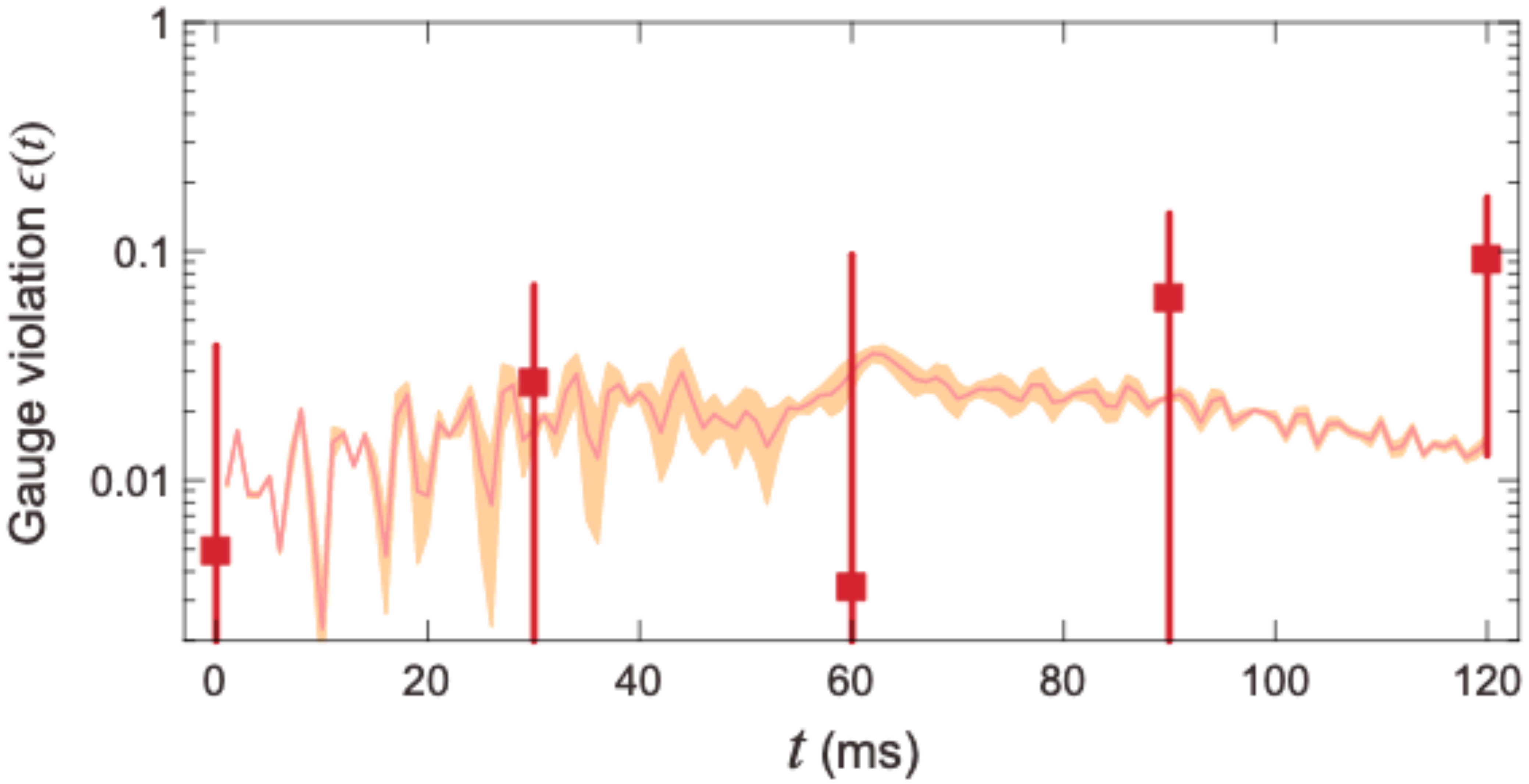
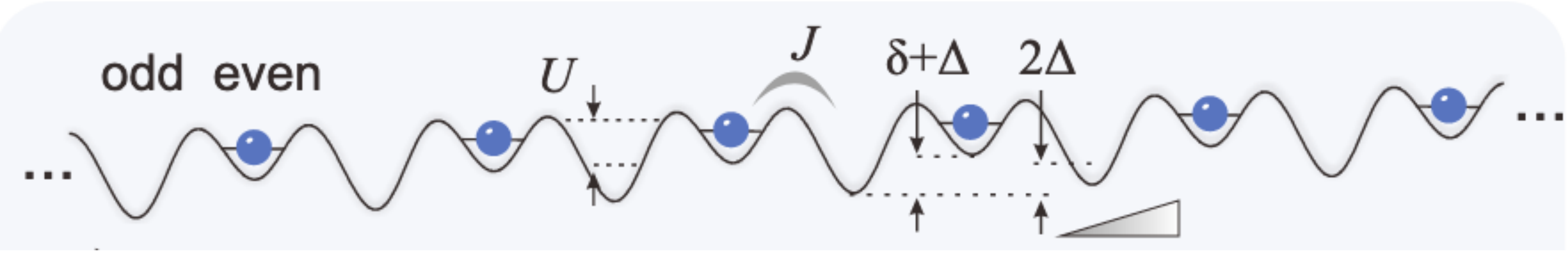




B. Yang et al. Nature **587**, 392-396 (2020)

Bosonic atoms in tilted optical superlattices



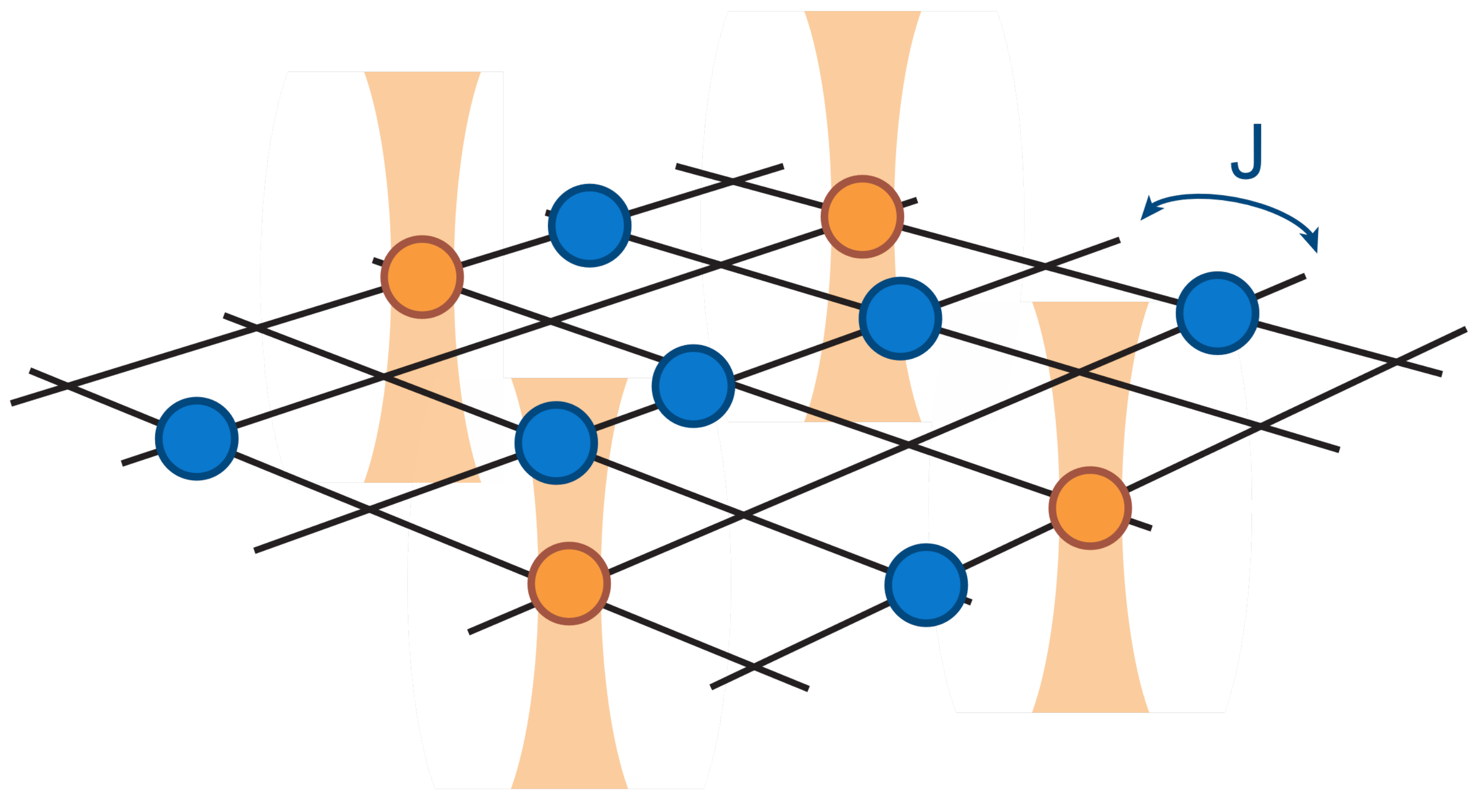
B. Yang *et al.* Nature **587**, 392-396 (2020)
Z.-Y. Zhou Et al., Science 377, 311 (2022)
H.-Y. Wang Et Al., Phys. Rev. Lett. **131**, 050401 (2023)

Our goal:

- Simulate gauge field & fermionic matter
- Simulation of 2D QLMs
- Extension to non-Abelian

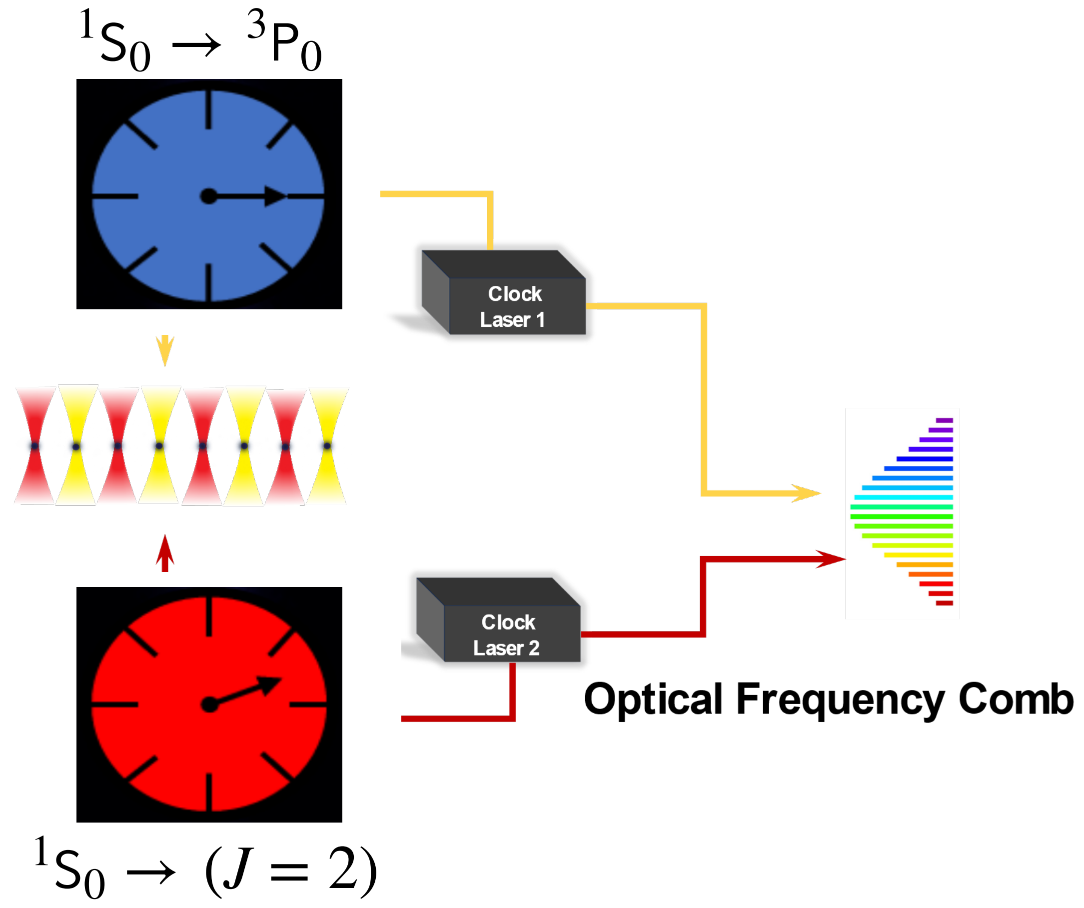
Quantum science with neutral Yb atoms

Fermionic quantum simulation



- Simulation of QED in 2D, towards non-Ablian LGTs
- Fast repetition rates
- State-dependent mobility
- Quantum simulation of open systems

Fundamental physics & quantum metrology



- Searches for new physics using precision spectroscopy
- $\alpha-$variation
- Local position / Lorentz invariance
- Quantum mechanics & gravity
- Quantum enhanced metrology

Höhn, ..., Aidelsburger, PRA **108**, 053325 (2023); Höhn, ..., Aidelsburger, arXiv:2412.14163; Kroeze, ..., Aidelsburger, arXiv:2506.09031

The Team

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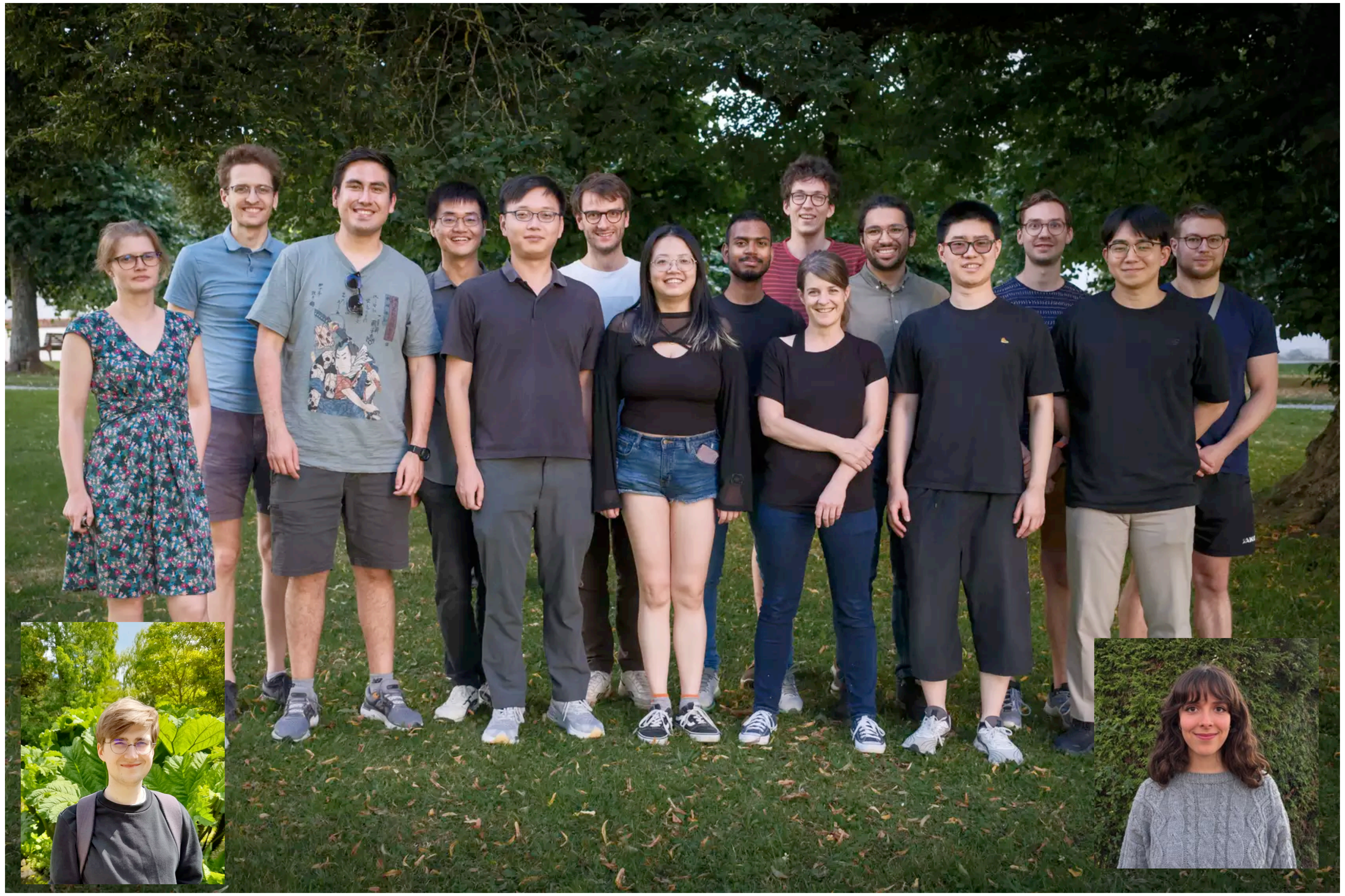
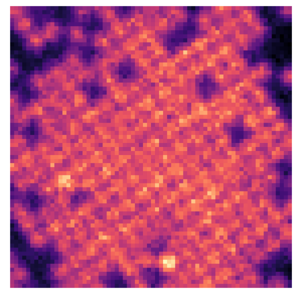
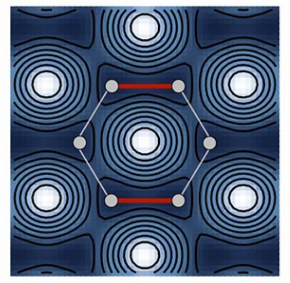
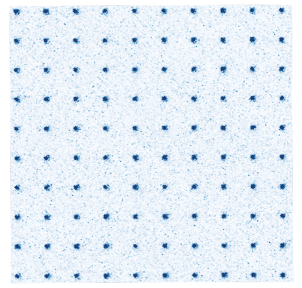



Cs quantum gas microscope


K honeycomb lattice


Yb hybrid tweezer-lattice

Ryd-Yb

Yb double-frequency clock

Thank you