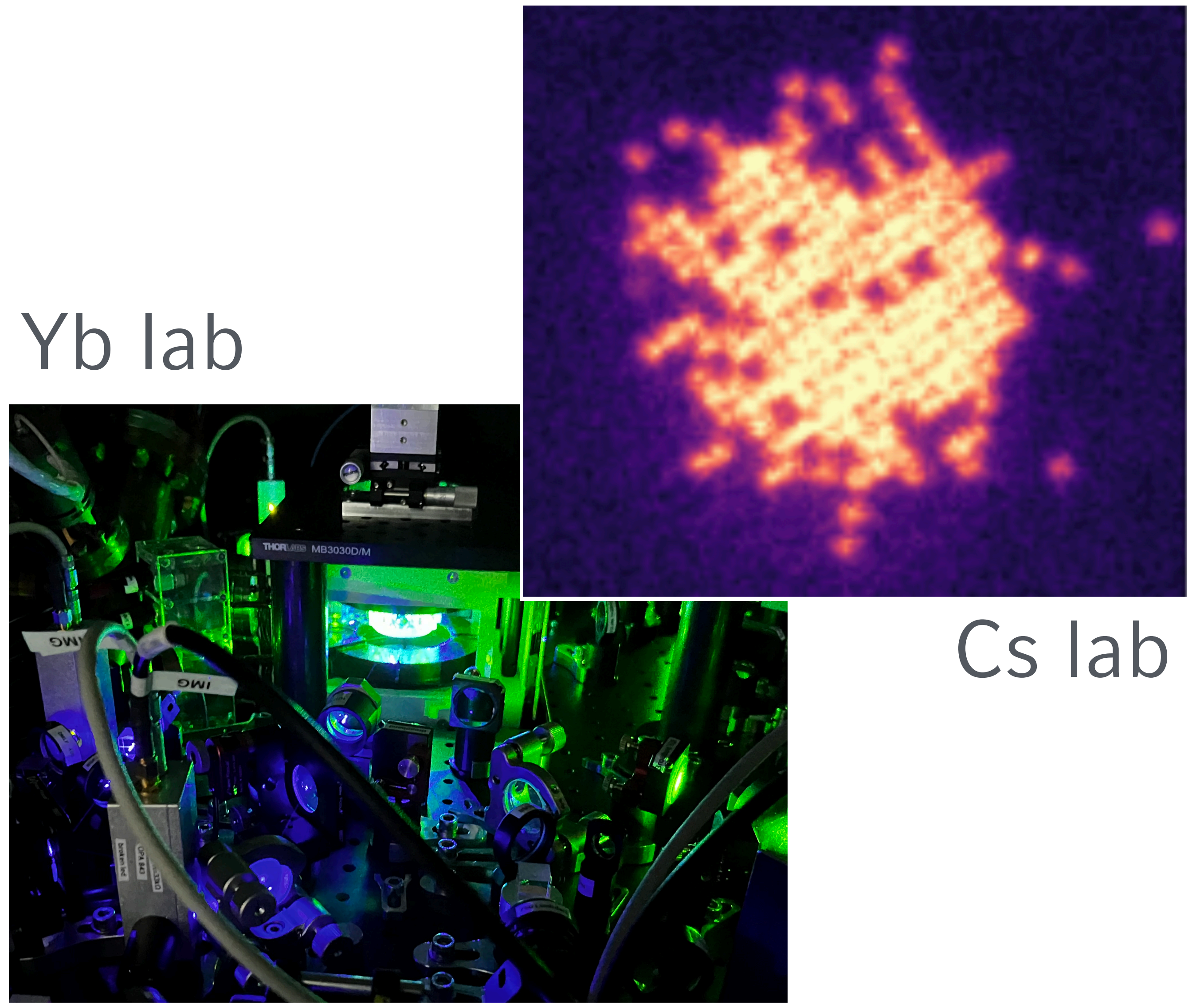
Quantum simulation -
Engineering quantum systems atom-by-atom

Monika Aidelsburger
Ludwig-Maximilians Universität München
Munich Center for
Quantum Science & Technology

www.sqm.physik.lmu.de

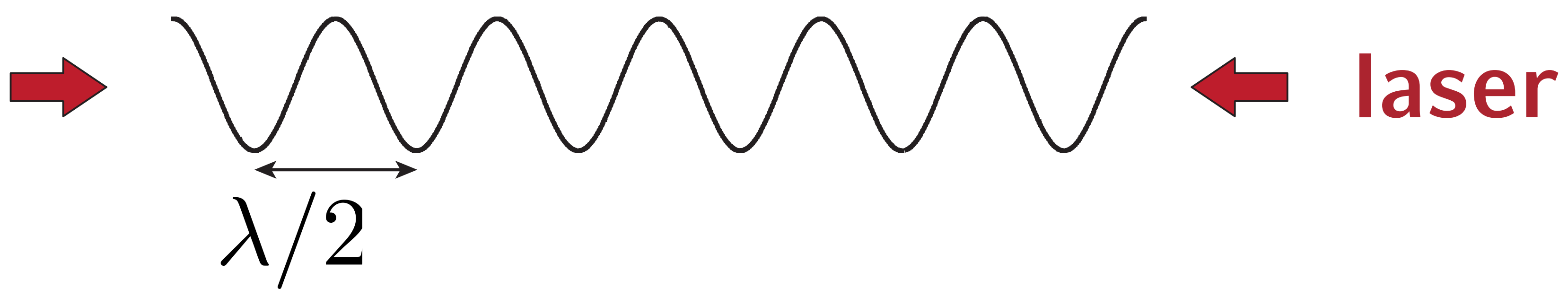


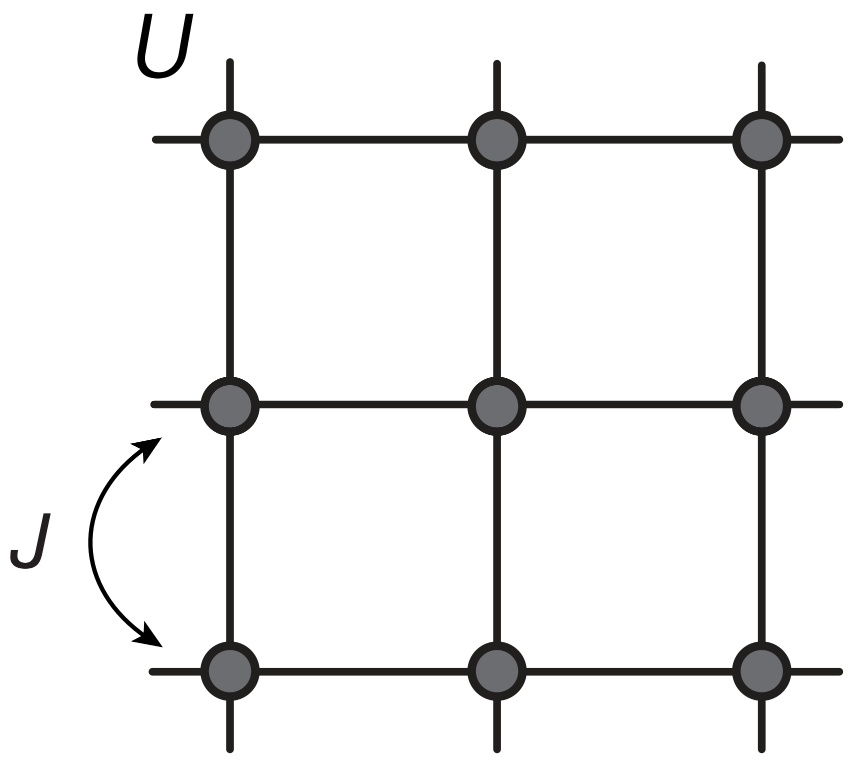
LMU LUDWIG-MAXIMILIANS-UNIVERSITÄT MÜNCHEN
MCQST
MUNICH QUANTUM CENTER
Munich Quantum Valley
MPQ
GEFÖRDERT VOM Bundesministerium für Bildung und Forschung
DFG Deutsche Forschungsgemeinschaft
erc European Research Council

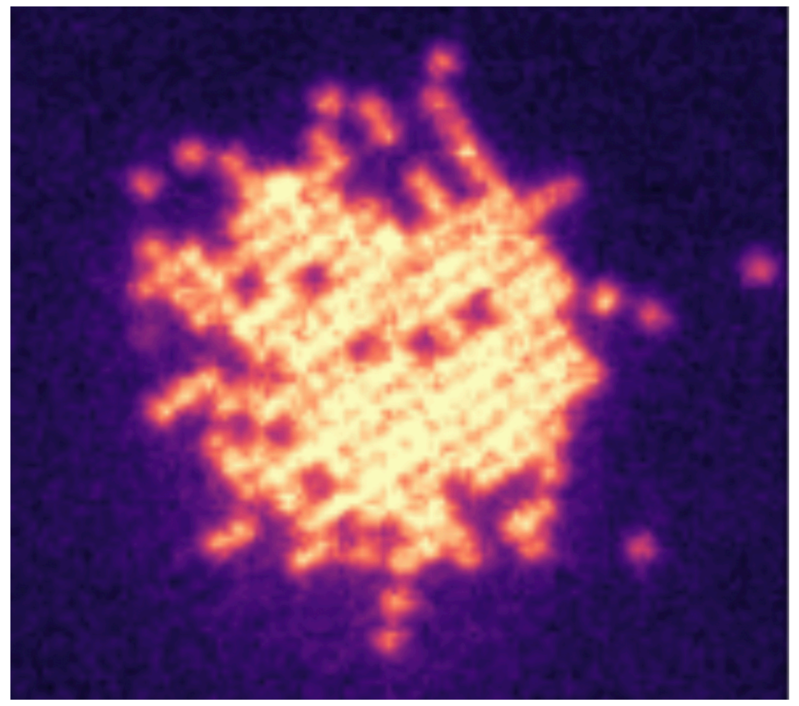
Motivation

Quantum simulation with ultracold atoms in optical lattices:

- Atoms confined in periodic potentials







Cs atoms

- Quantum simulation of Hubbard models

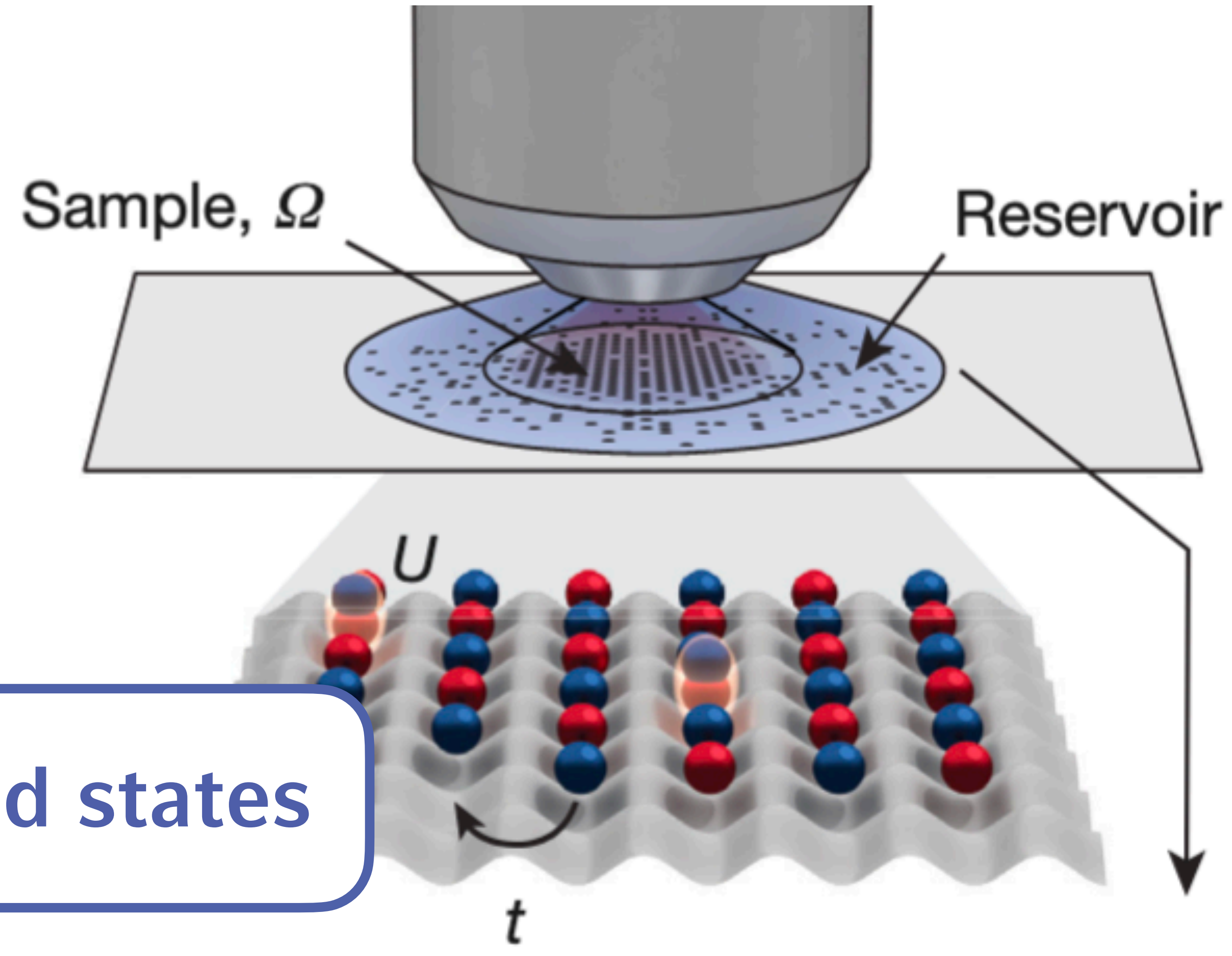
- Access to local observables using quantum gas microscopes

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

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

Quantum simulation with neutral atoms

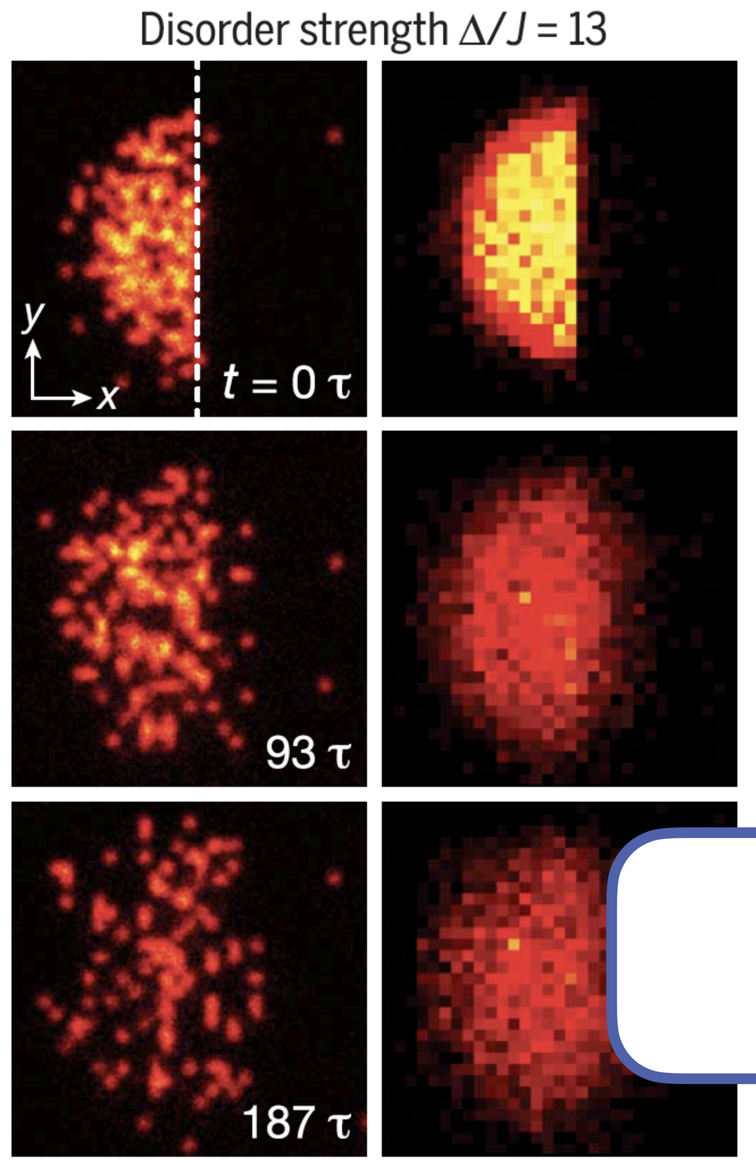
Anti-ferromagnetic correlations in the Fermi-Hubbard model:



Ground states

A. Maruzenko, ... M. Greiner, Nature (2017)

Thermalization of isolated quantum-many body systems:



Dynamics

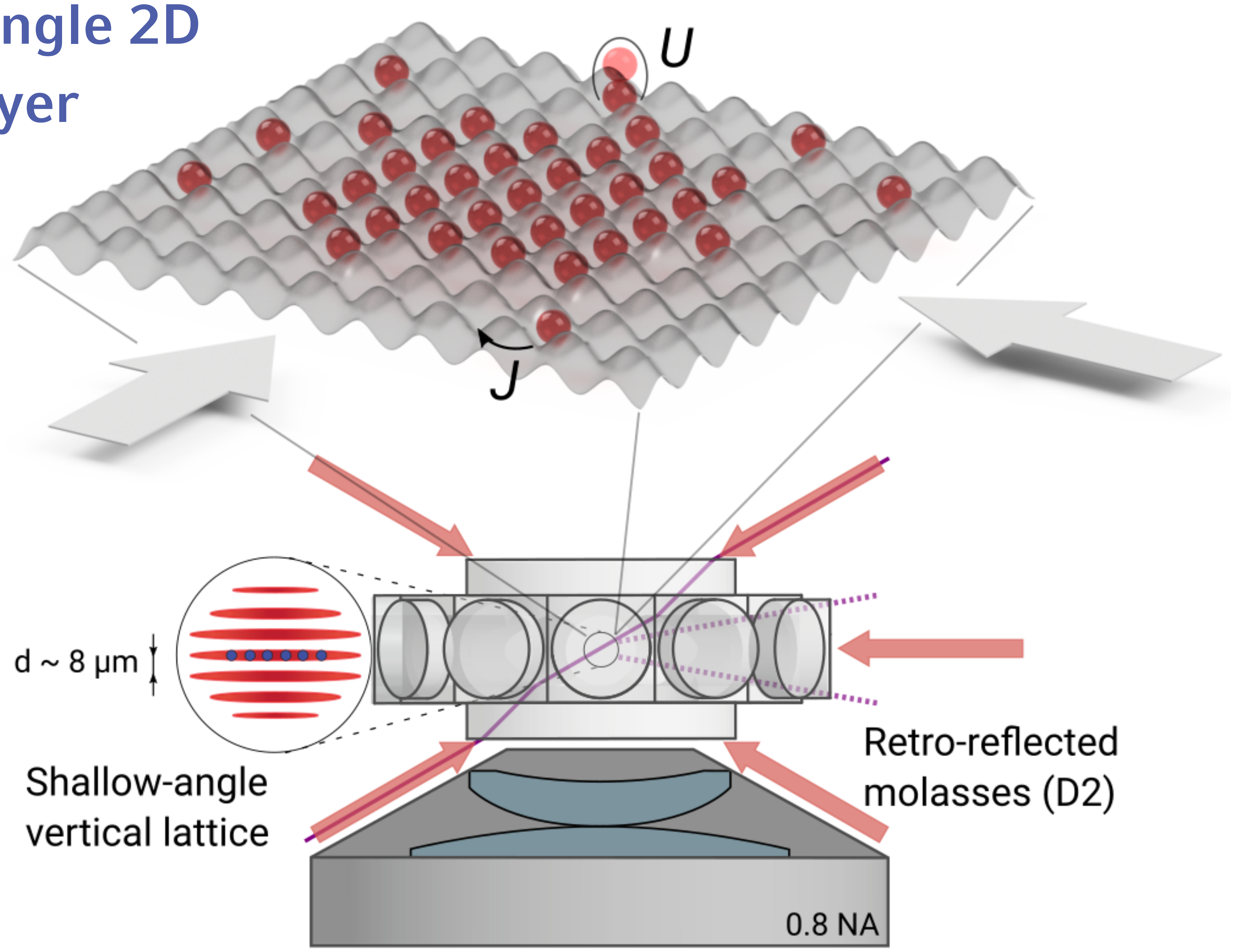
J. Y. Choi, ..., I. Bloch, Science **352**, 1547 (2016)

Direct implementation of Hamiltonian $|\psi(t)\rangle = \mathrm{e}^{-i\hat{H}t/\hbar}|\psi_0\rangle$

Quantum Gas Microscopy

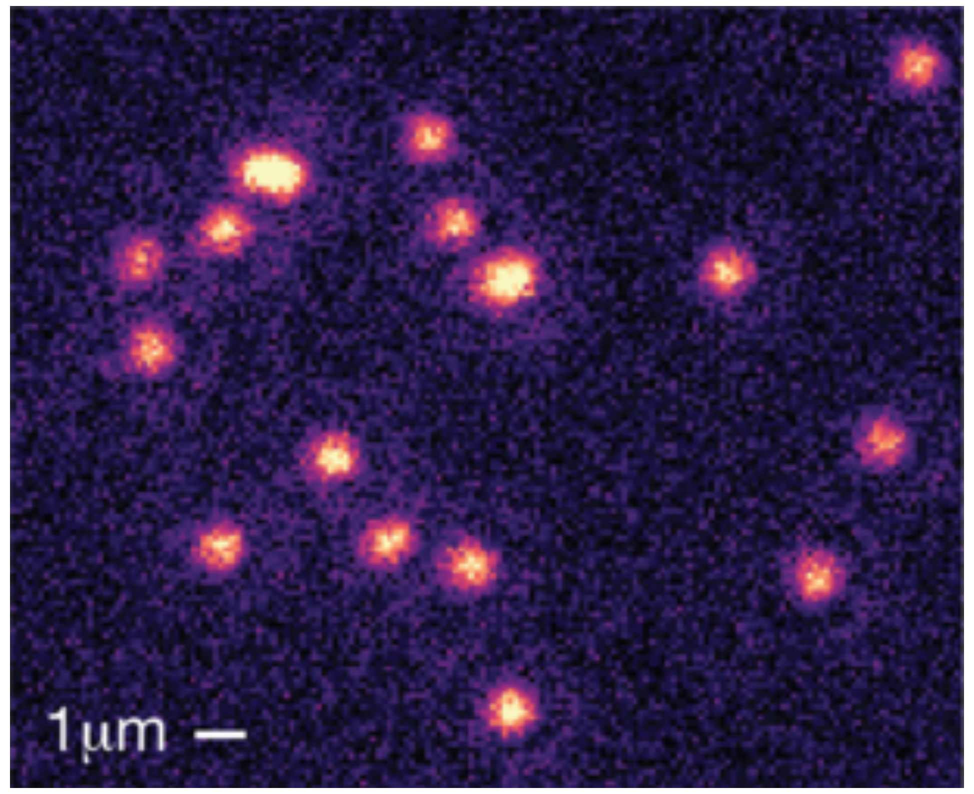
Quantum Gas Microscopy

Single 2D layer



High-NA objective

Fluorescence imaging in deep lattices

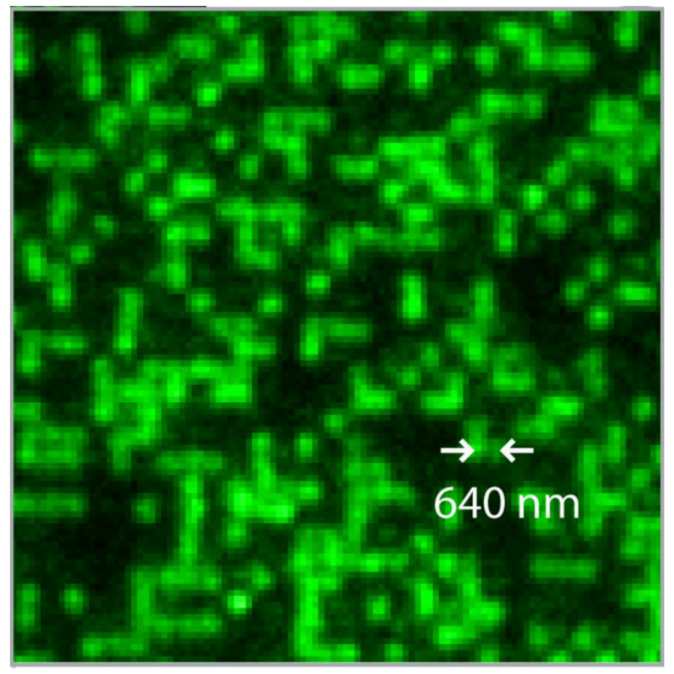


- Single-site resolved observables (correlations, full counting statistics, ...)
- Site-selective addressing

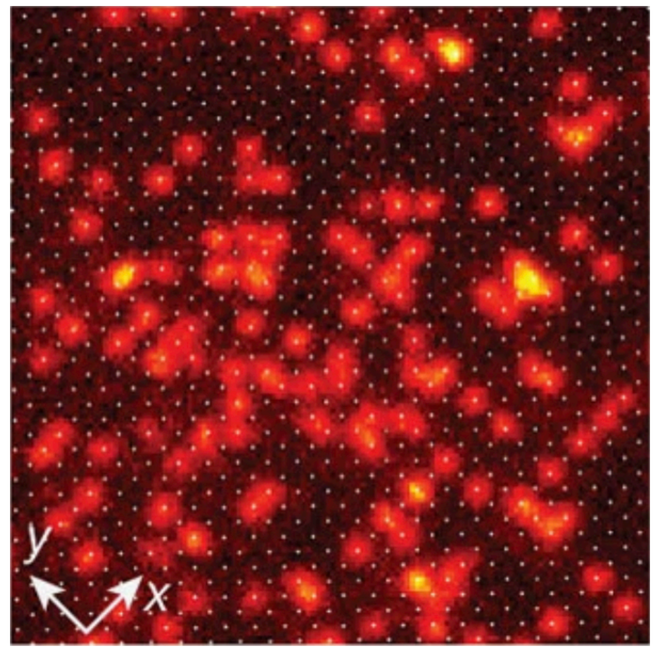
W. S. Bakr et al., Nature **462**, 74 (2009); J. F. Sherson et al. Nature **467**, 68 (2010)
L. Cheuk et al. PRL **114**, 193001 (2015); E. Haller et al. Nat. Phys. **11**, 738 (2015); M. F. Parsons et al., PRL **114**, 213002 (2015), ...

Quantum Gas Microscopy

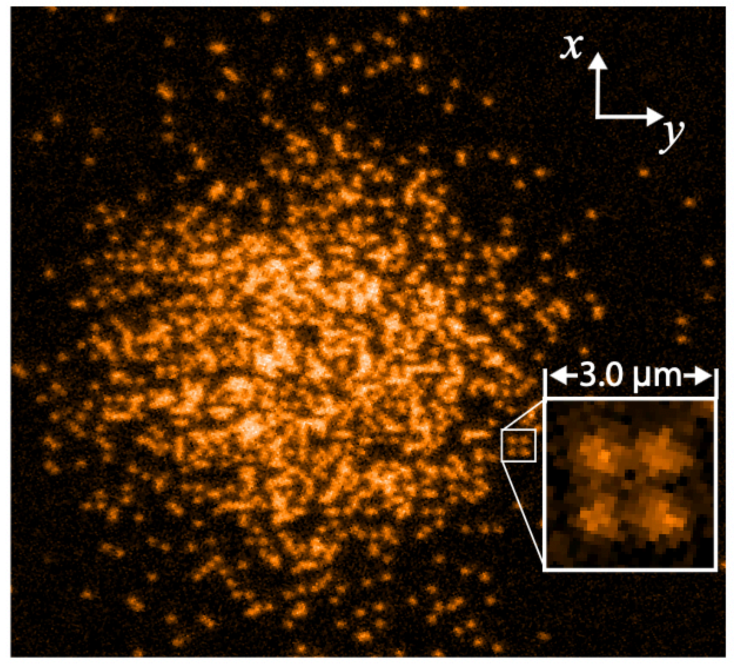
Selected examples:



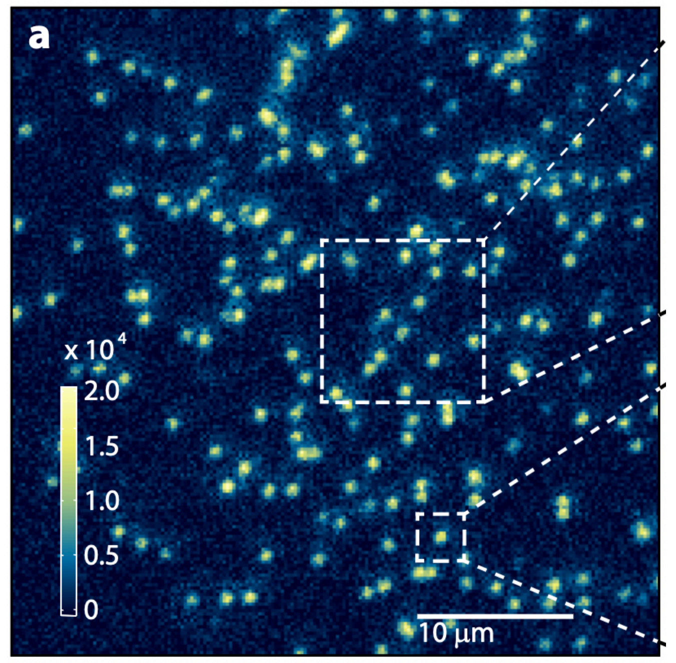
Rb atoms, Greiner



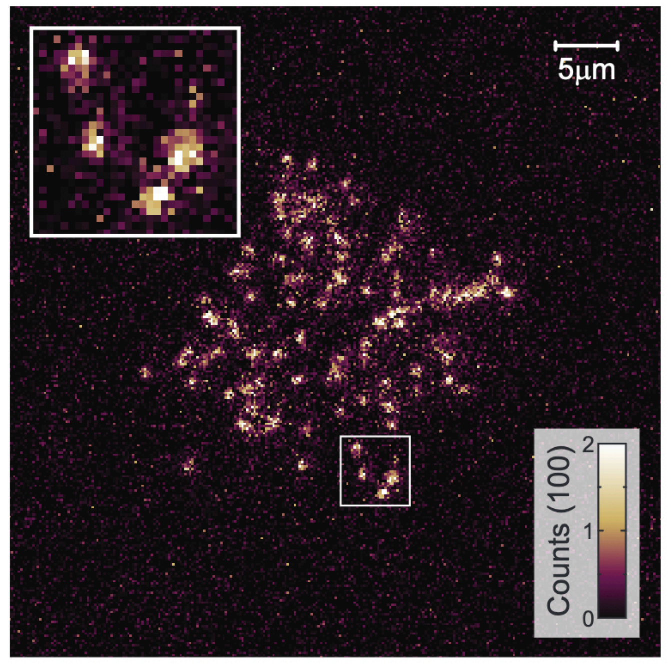
Rb atoms, Bloch



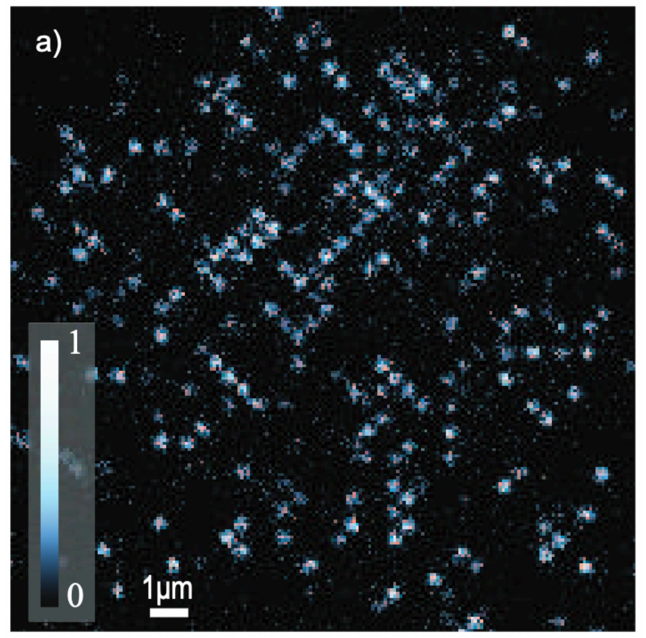
K atoms, Zwierlein



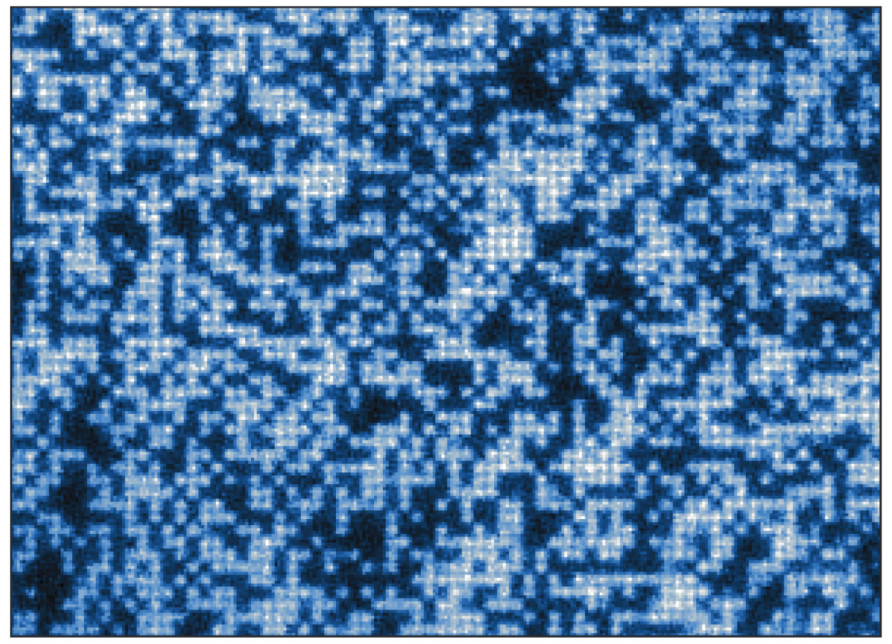
K atoms, Kuhr



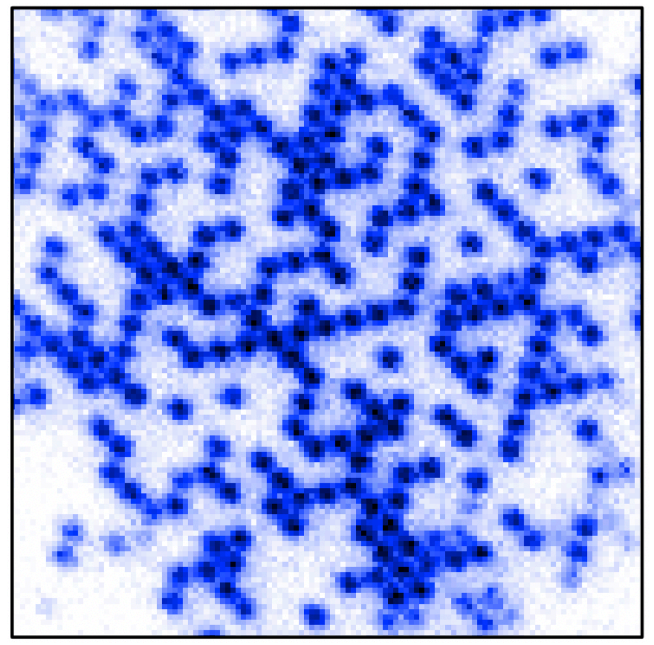
K atoms, Thywissen



Yb atoms, Kozuma



Li atoms, Choi

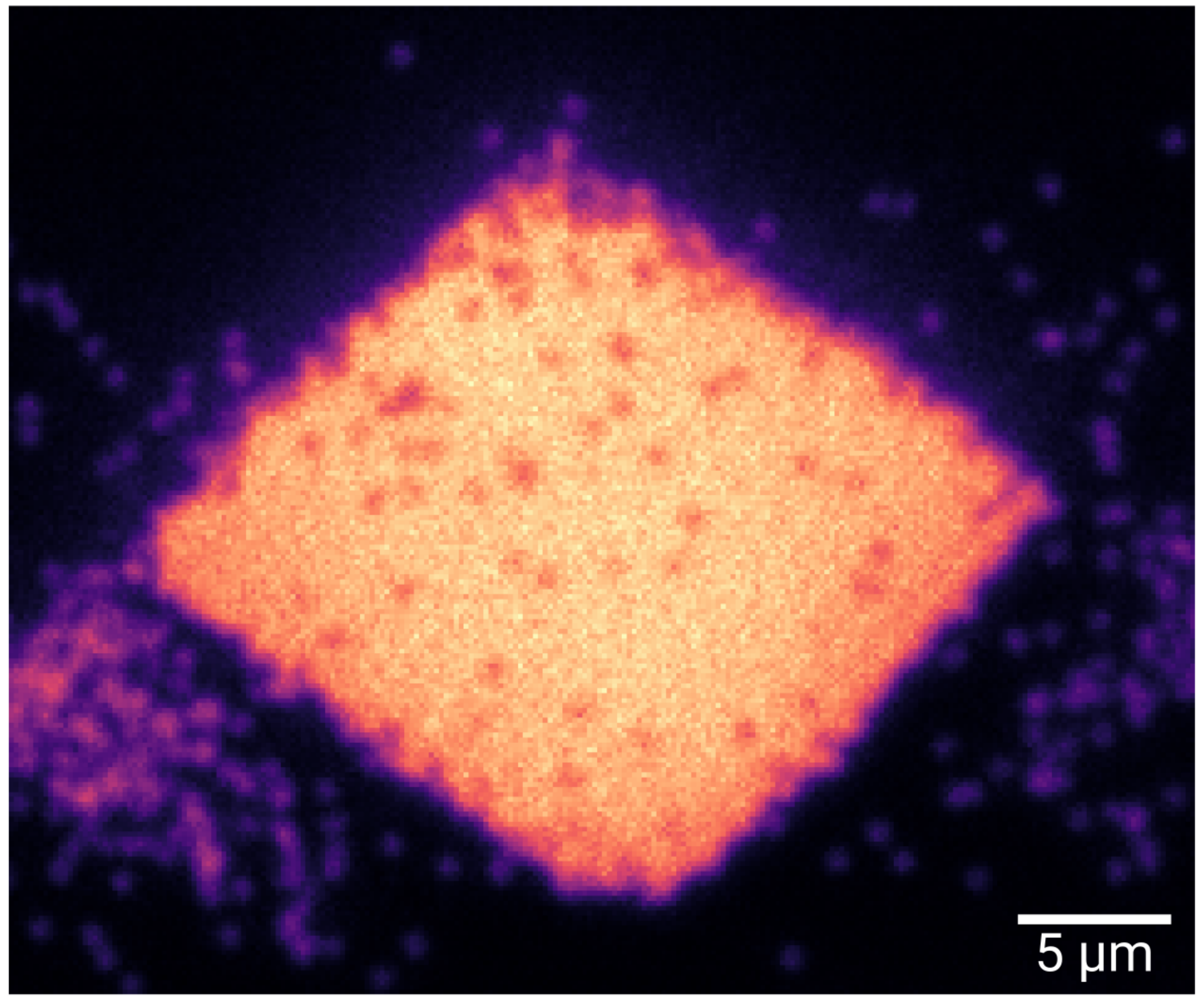


Li atoms, Schauss

- Large homogeneous systems
- High fidelity preparation & detection
- Novel model Hamiltonians
- Large energy scales

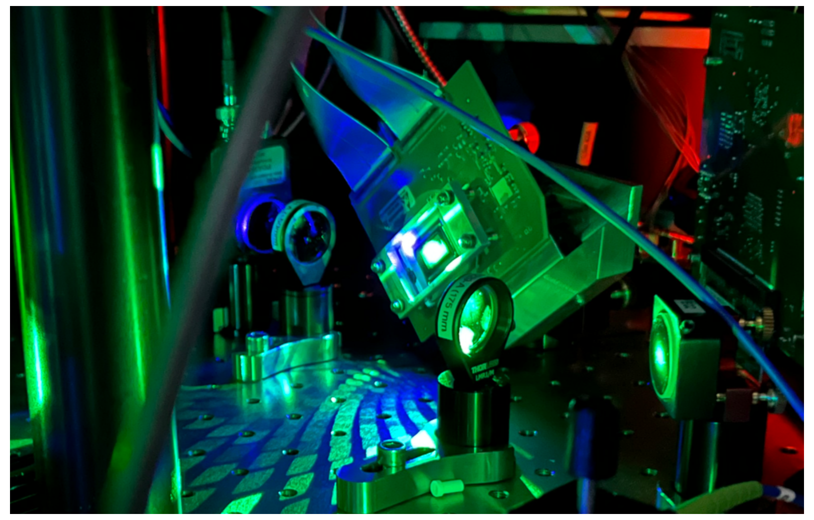
Review: C. Gross and W. Bakr, Nature Phys. (2021)

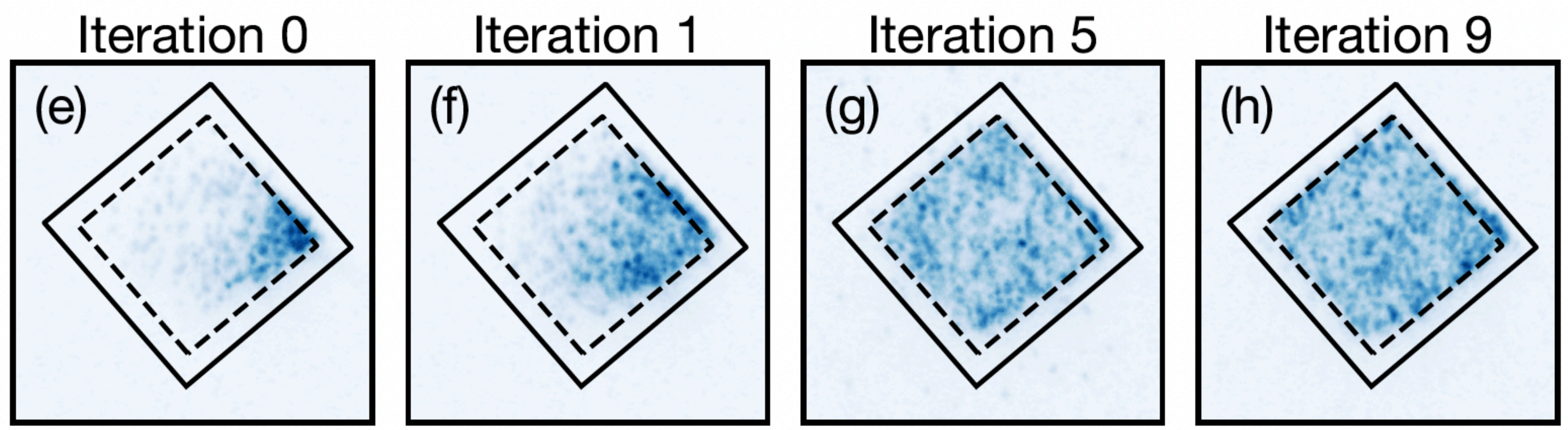
Realization of large homogeneous systems



$\sim 50 \times 50$ sites, 2500 atoms
~ 0.98 filling

Potential shaping using a digital micromirror device



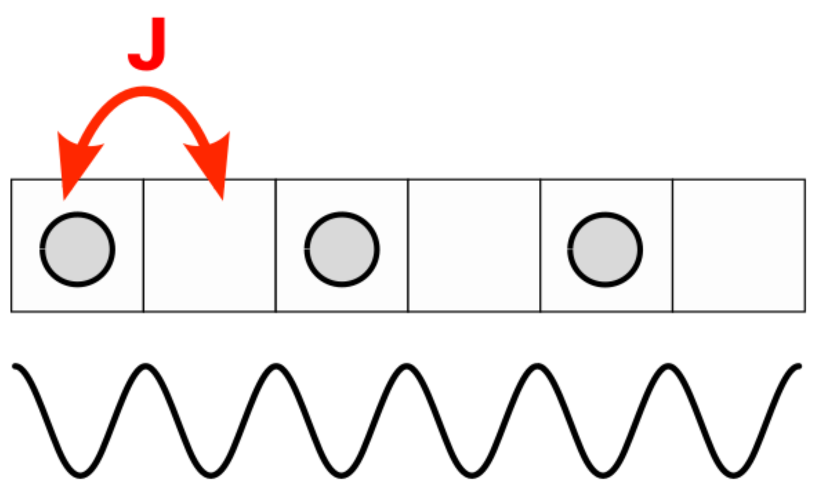


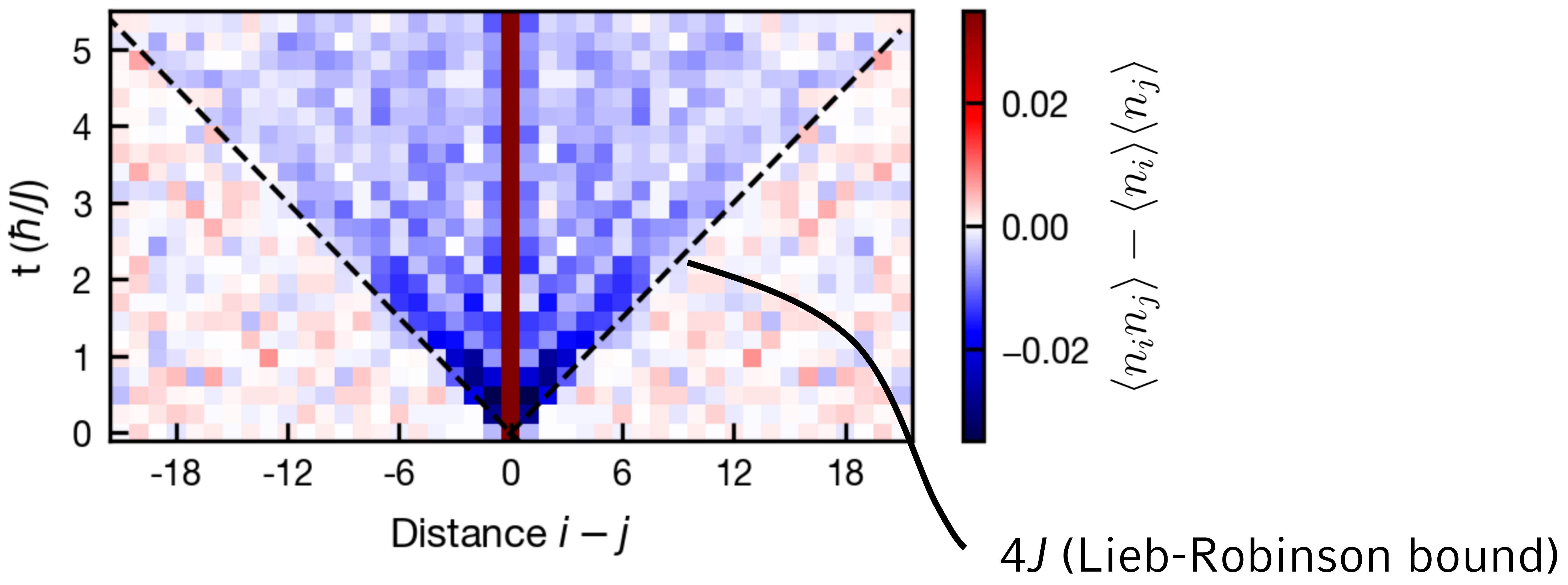
A. Impertro, J. F. Wienand, S. Häfele, H. von Raven, S. Hubele, T. Klostermann, C. R. Cabrera, I. Bloch, MA, arXiv:2212.11974
T. Klostermann et al, Phys. Rev. A 105, 2022; PhD Theses Klostermann & von Raven; Master thesis Hubele

Benchmarking via thermalization dynamics

Hard-core bosons in 1D

Initial state: CDW



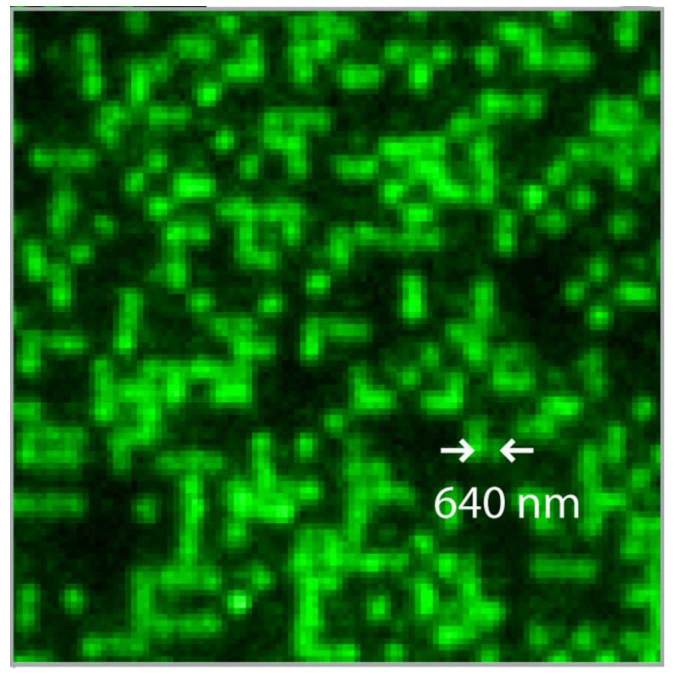


Ballistic spreading of density-density correlations over large distances!

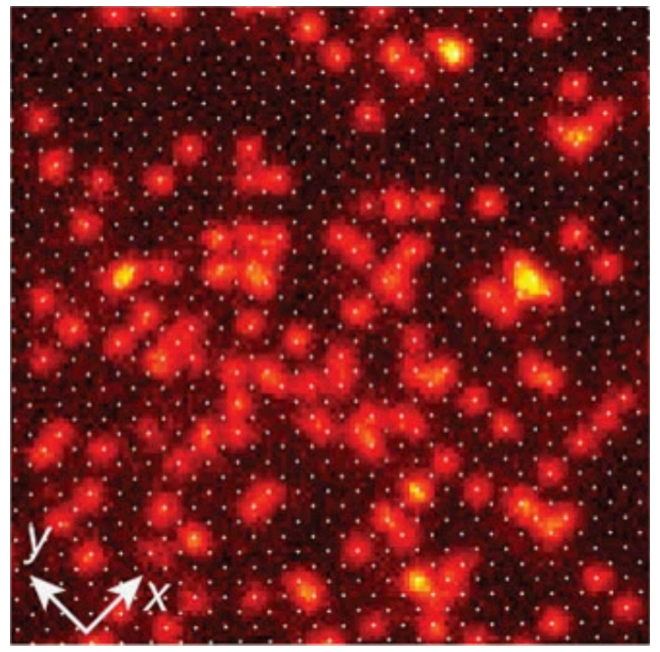
Preliminary!

Quantum Gas Microscopy

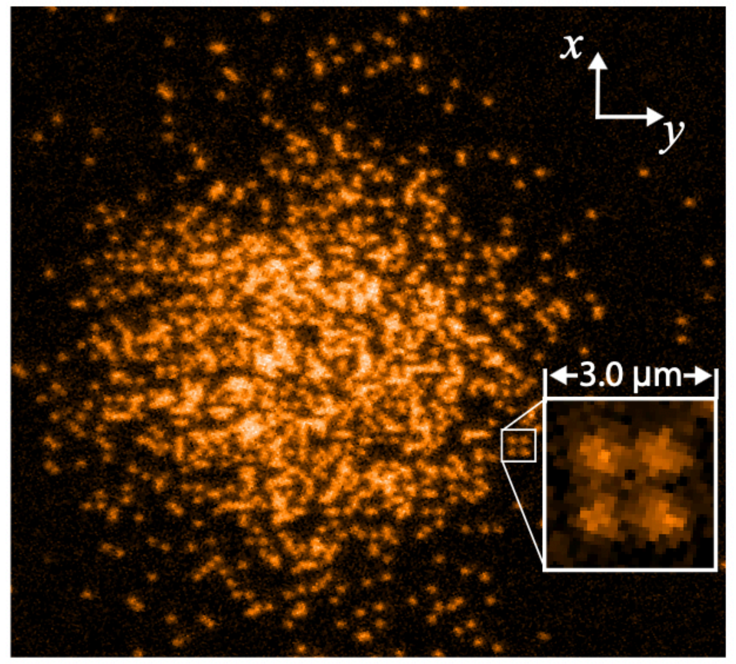
Selected examples:



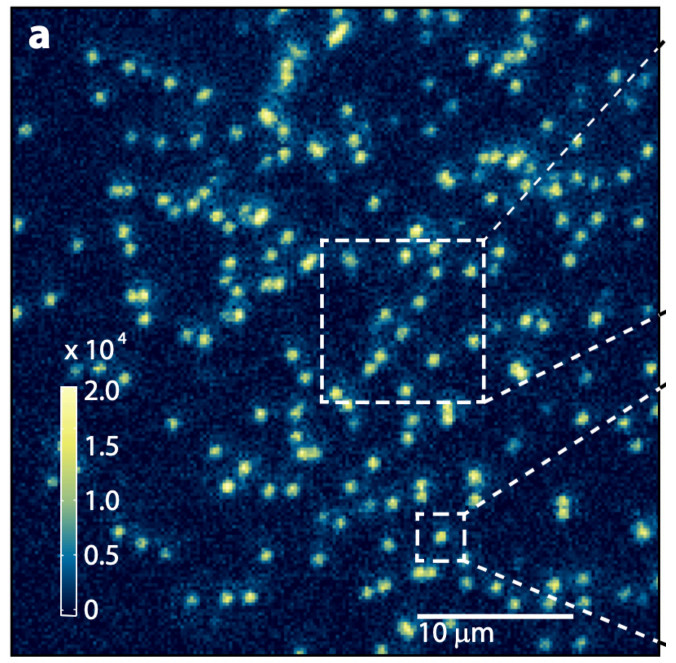
Rb atoms, Greiner



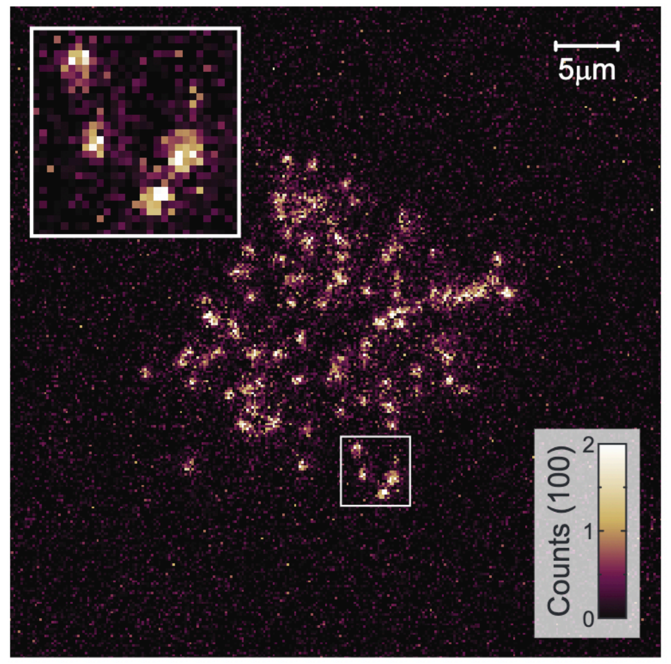
Rb atoms, Bloch



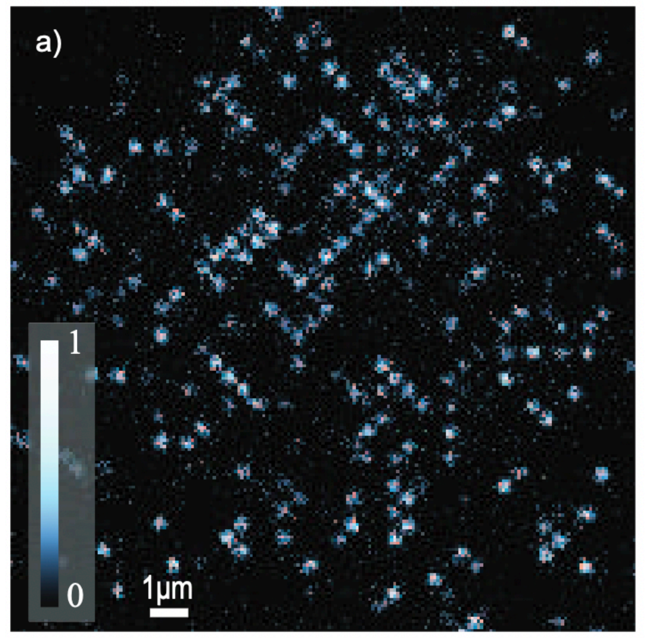
K atoms, Zwierlein



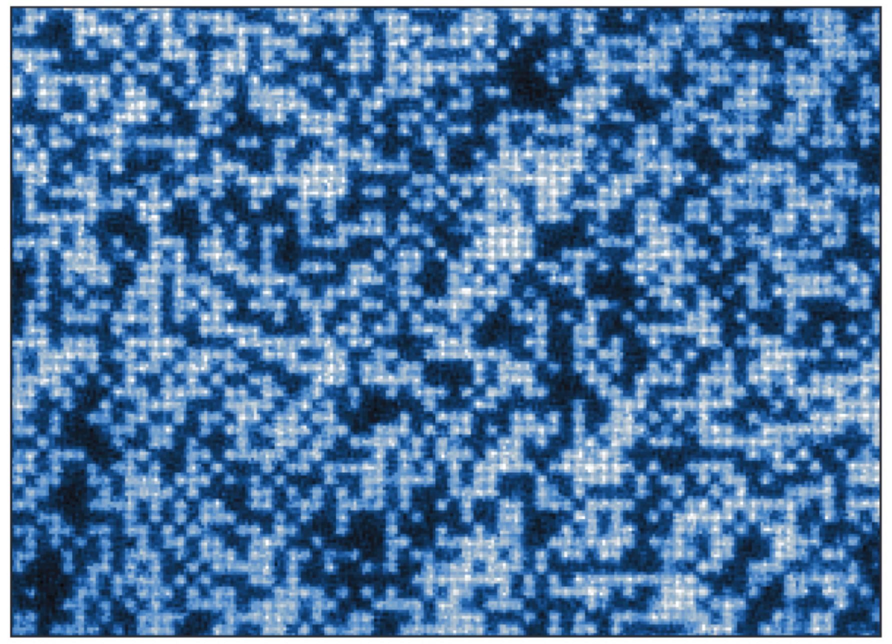
K atoms, Kuhr



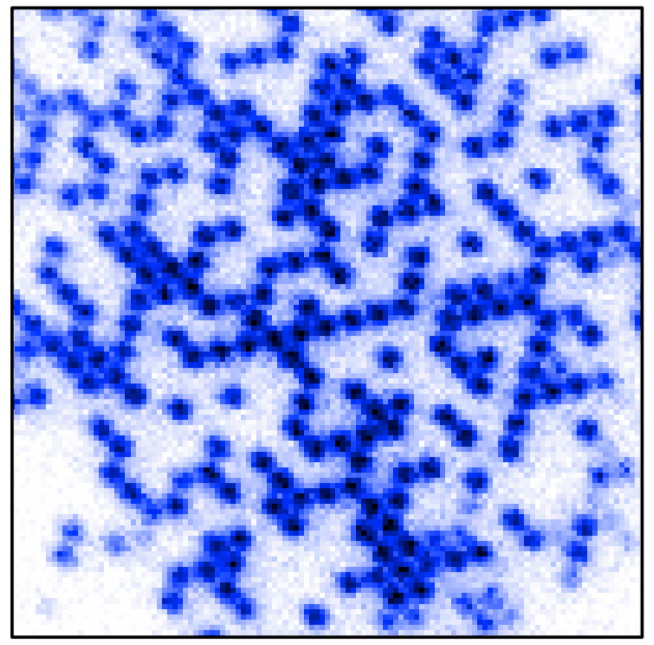
K atoms, Thywissen



Yb atoms, Kozuma



Li atoms, Choi



Li atoms, Schauss

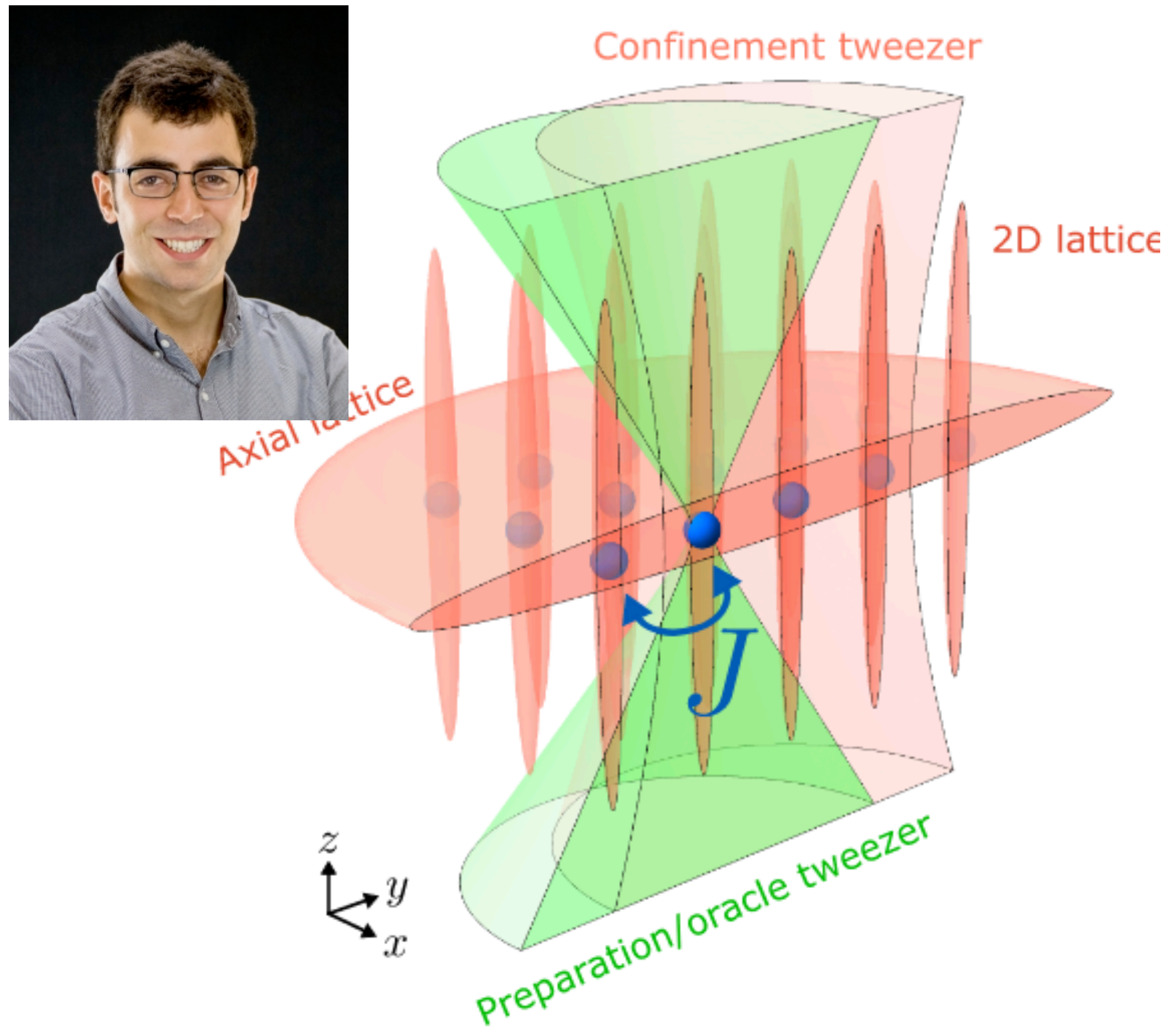
- Repetition rate
- Local control

Review: C. Gross and W. Bakr, Nature Phys. (2021)

Repetition rate ~20s
Magneto-optical trap
& Raman cooling: ~μK
Transport
Science cell:
~10^-11 mbar / ~nK
degenerate quantum gas
Atom
source
Bose-Einstein
condensate
Degenerate
Fermi Gas

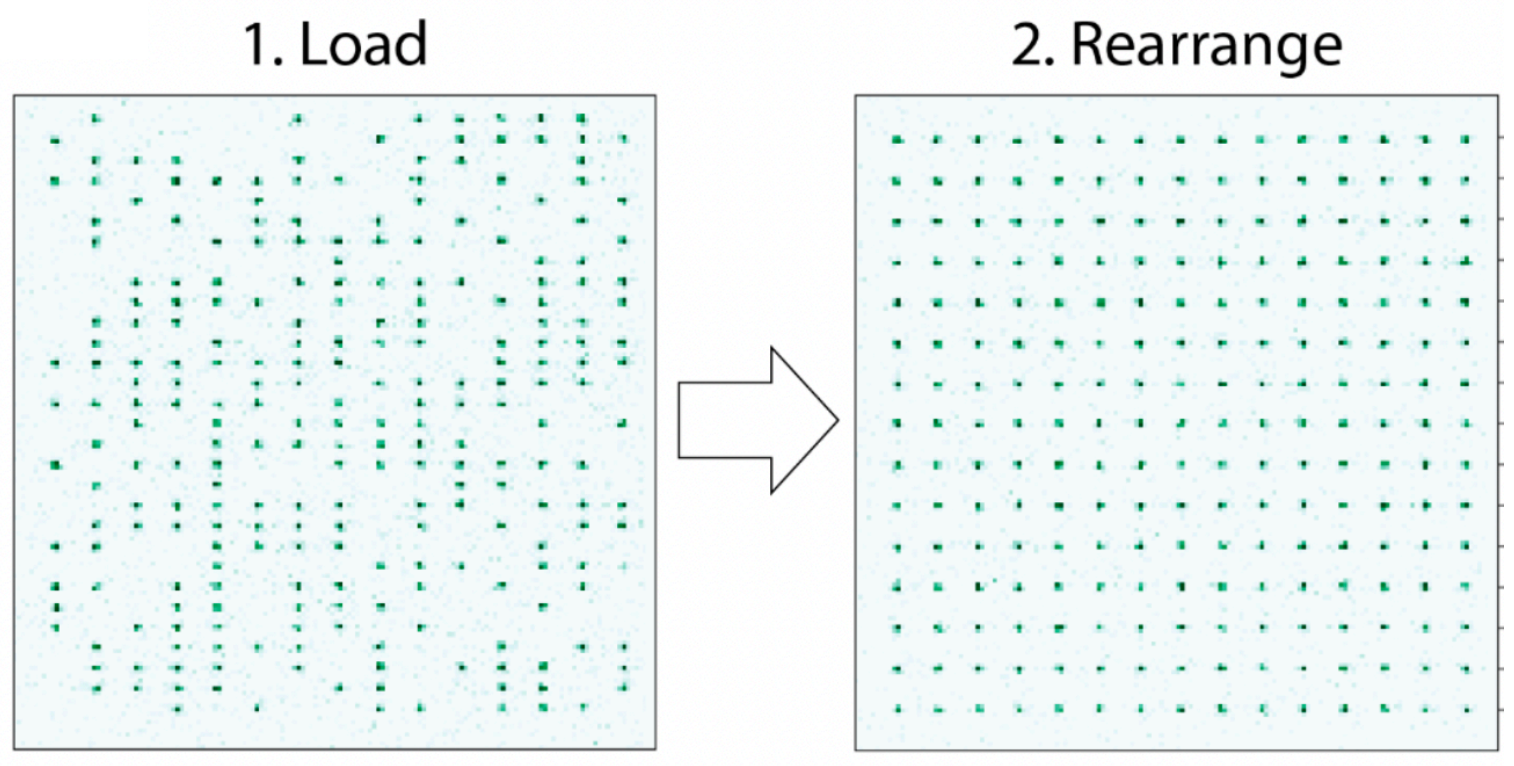
Tweezer-assisted preparation

Tweezer programmable quantum walks



Young,..., Kaufman, Science **377**, 885 (2022)

- Fast cycle times by direct laser cooling in deep optical traps
- Initial states require rearrangement of atoms



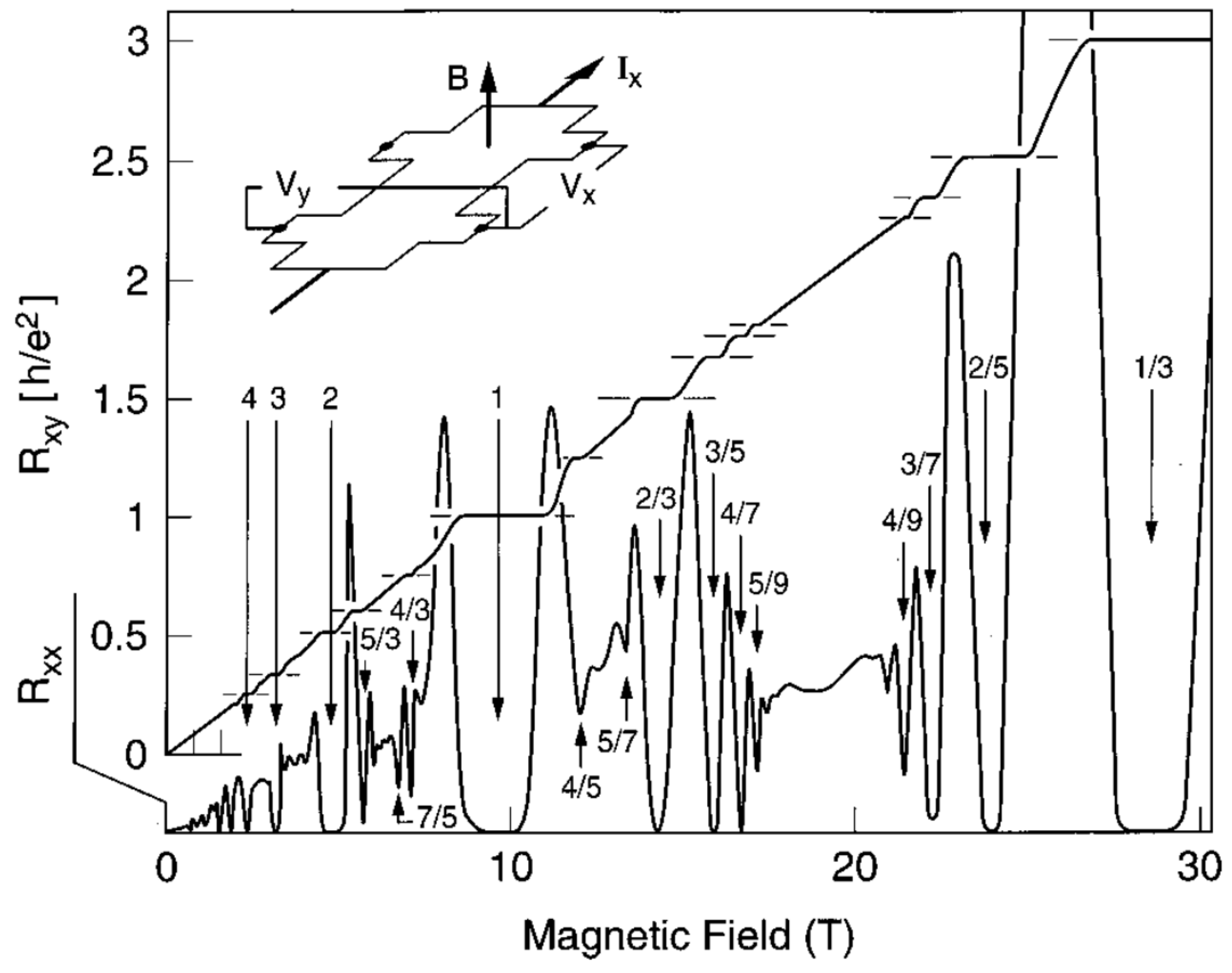
Ebadi, ..., Lukin, Nature **595**, 227 (2021)

see also work by C. Regal and W. Bakr

What can we simulate?

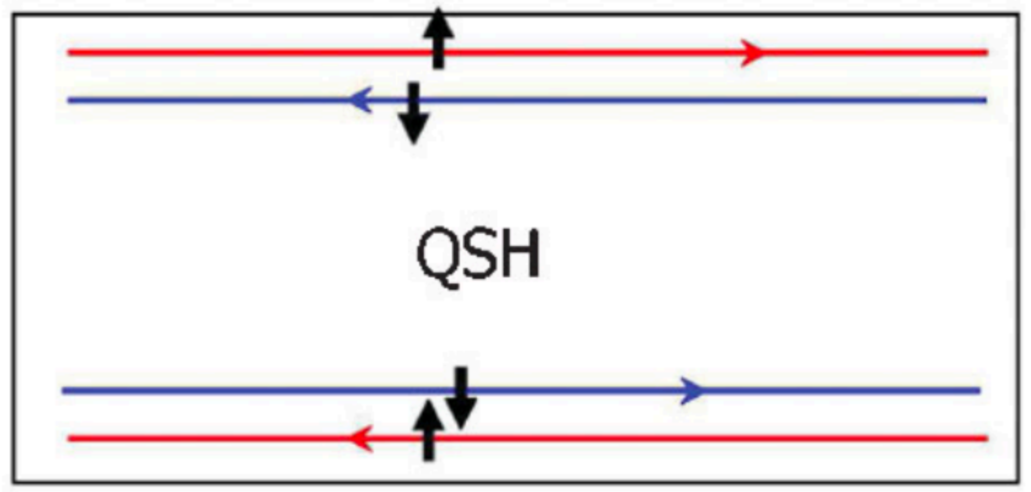
Topological phases of matter

Integer & fractional quantum Hall insulators



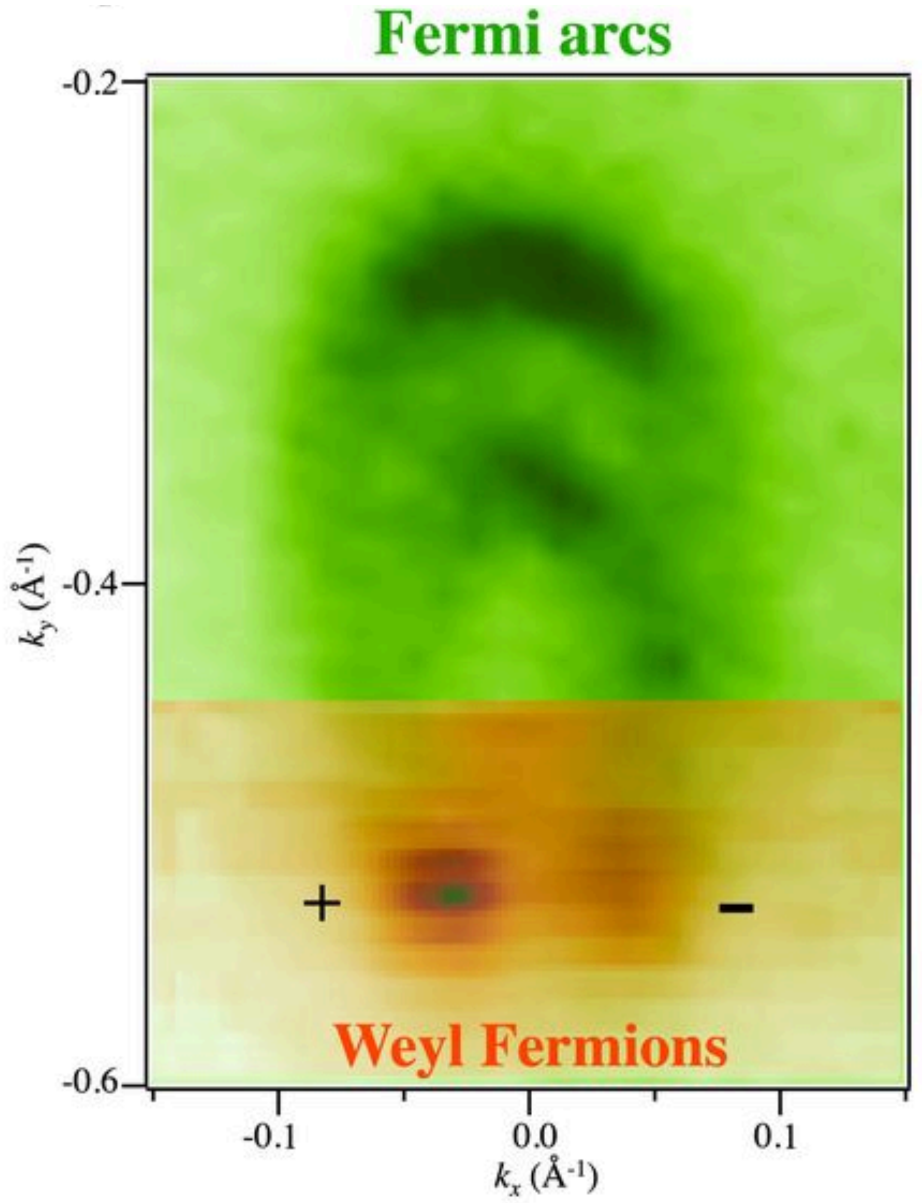
K. Klitzing, Rev. Mod. Phys. (1986)
Stormer et al., Rev. Mod. Phys. (1999)

Topological insulators in 2D & 3D



M. König et al., Science (2007)
A. Roth et al., Science (2009)

Weyl semimetals



L. Lu et al., Science (2015)
S.-Y. Xu et al., Science (2015)

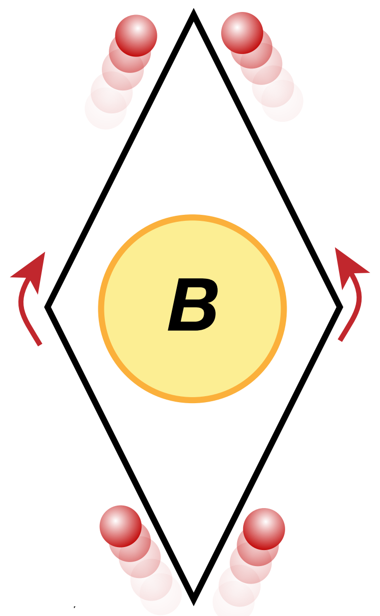
...

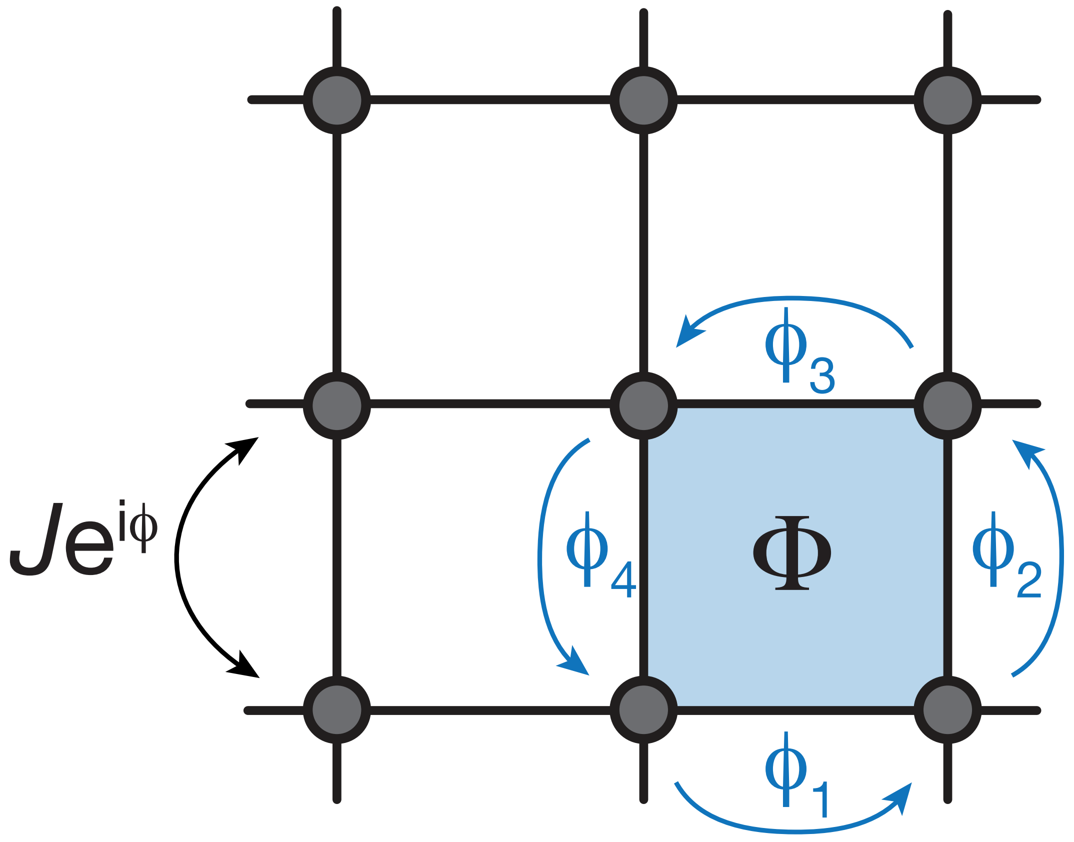
Review: X.-L. Qi & S.-C. Zhang, Rev. Mod. Phys. (2011)

Realizing artificial magnetic fields

Non-interacting lattice Hamiltonian:

$$\hat{H} = -\sum_{\langle i,j \rangle} J_{ij} \hat{a}_i^\dagger \hat{a}_j + \text{h.c.}$$





Charged particles in magnetic field
→ acquire geometric phase

Peierls substitution: $J_{ij} \rightarrow J_{ij} e^{i\phi_j}$

$$\phi_j = \frac{q}{\hbar} \int_{x_j}^{x_i} \mathbf{A} \mathrm{d}\mathbf{l}, \quad \mathbf{B} = \nabla \times \mathbf{A}$$

Phase around closed loop:

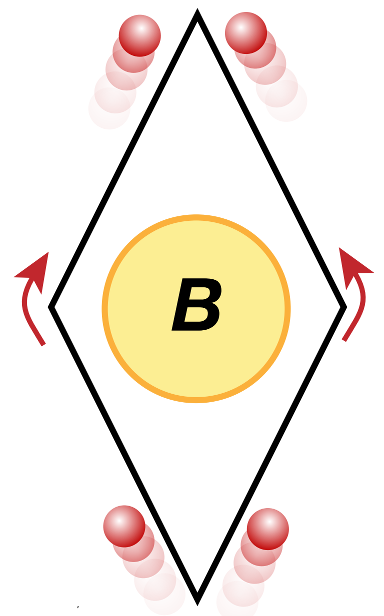
$$\Phi = \sum_{\square} \phi_j = 2\pi \frac{\Phi_B}{\Phi_0}$$

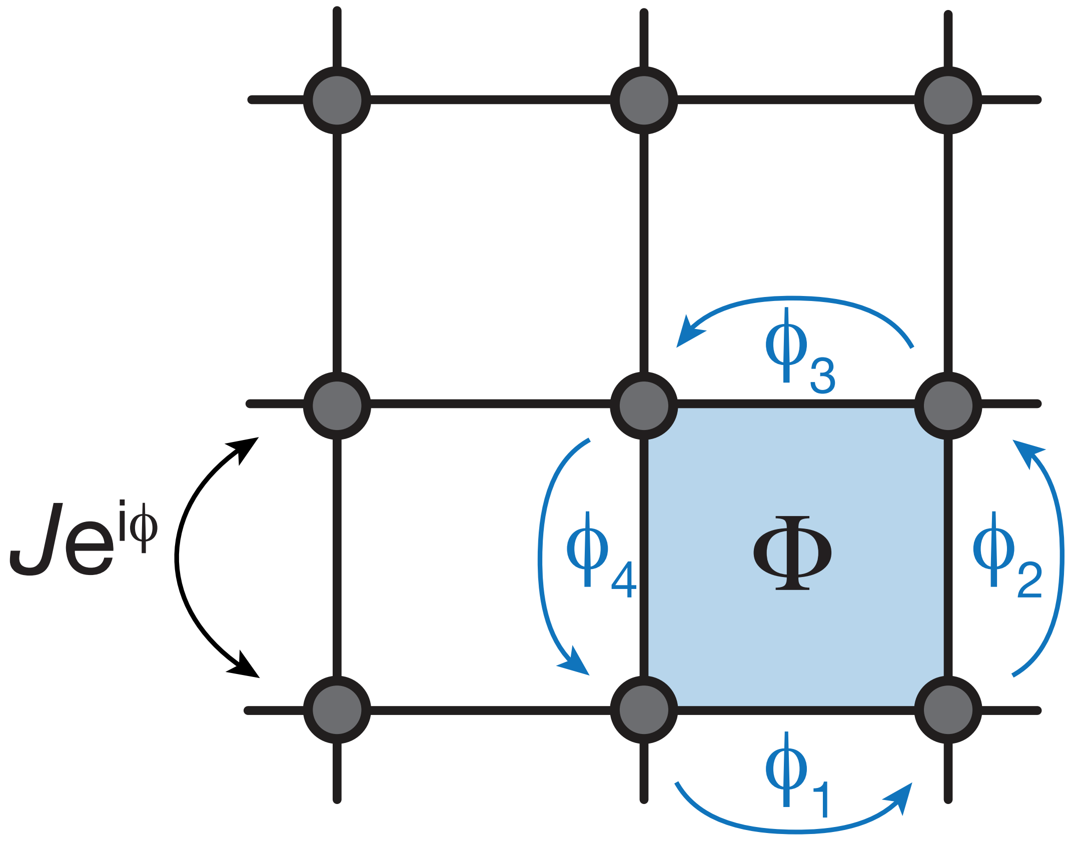
Φ_B: magn. flux
Φ_0= h/*q*: magn. flux quantum

Realizing artificial magnetic fields

Non-interacting lattice Hamiltonian:

$$\hat{H} = -\sum_{\langle i,j \rangle} J_{ij} \hat{a}_i^\dagger \hat{a}_j + \text{h.c.}$$





Charged particles in magnetic field
→ acquire geometric phase

⇒ *Large magnetic fields* on the order of one flux quantum (>1000 T)

Phase around closed loop:

$$\Phi = \sum_{\square} \phi_j = 2\pi \frac{\Phi_B}{\Phi_0}$$

Φ_B: magn. flux
Φ_0= h/q: magn. flux quantum

Floquet engineering

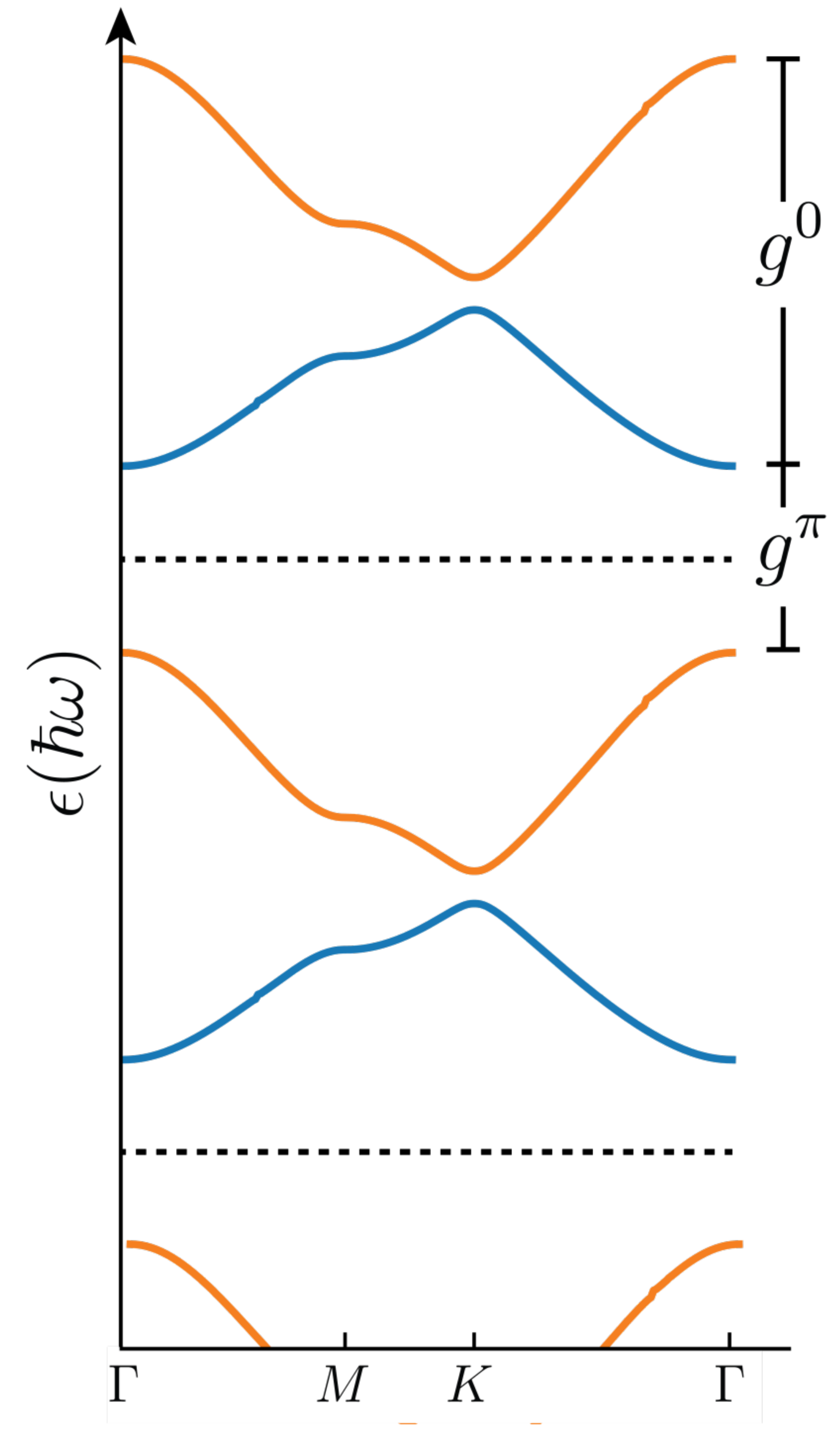
- Time-periodic driven Hamiltonian

$$\hat{H}(t) = \hat{H}(t+T)$$

- Stroboscopic time evolution governed by effective Floquet Hamiltonian $\hat{H}^F$

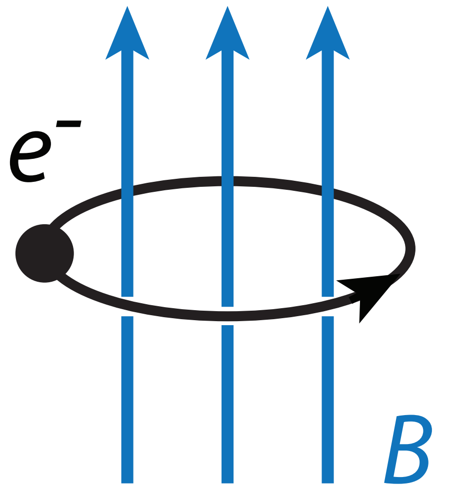
$$\hat{U}(T,0) = \exp\left(-\frac{i}{\hbar}T\hat{H}^F\right)$$

Engineer $\hat{H}_F$ with topological properties!

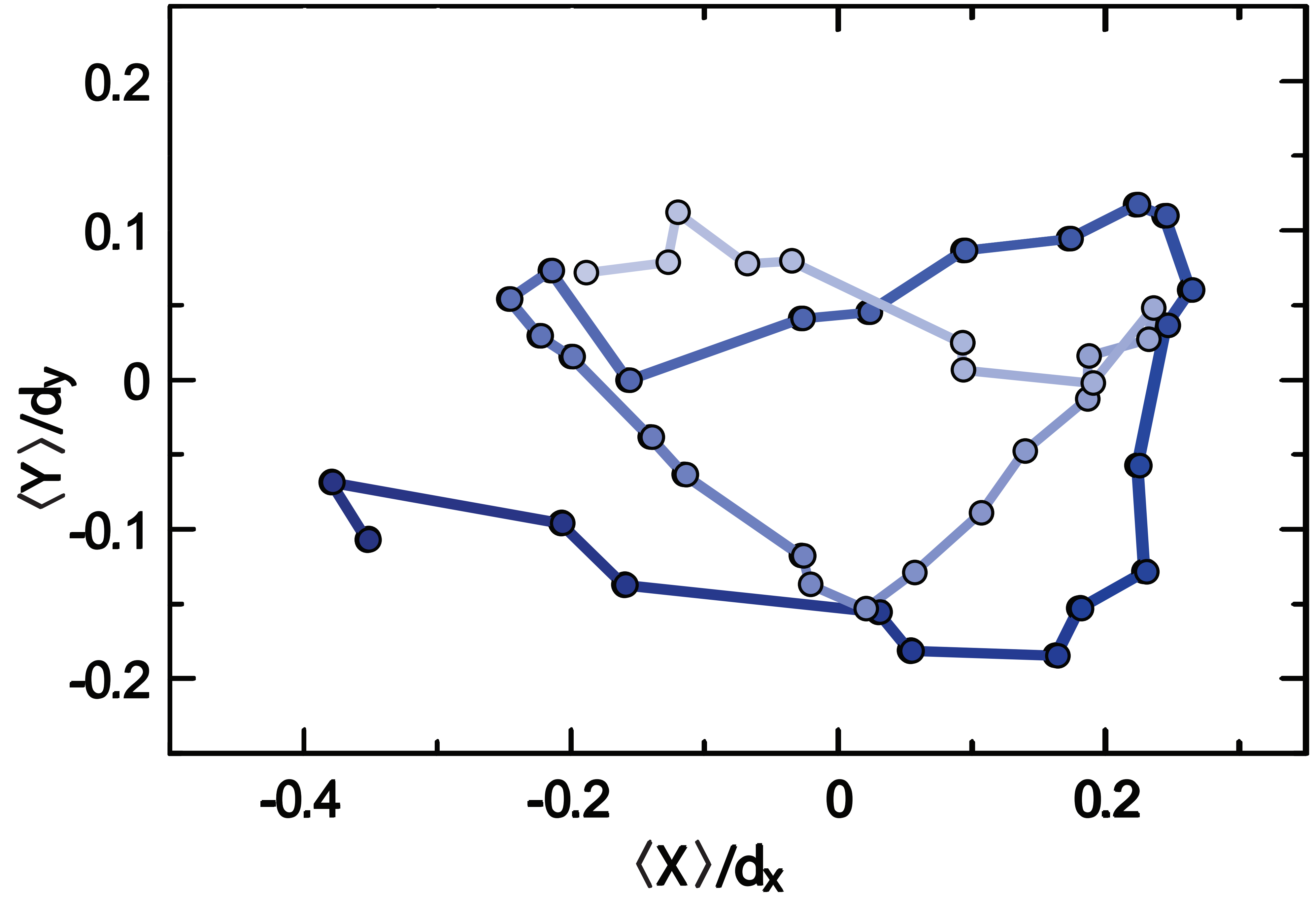


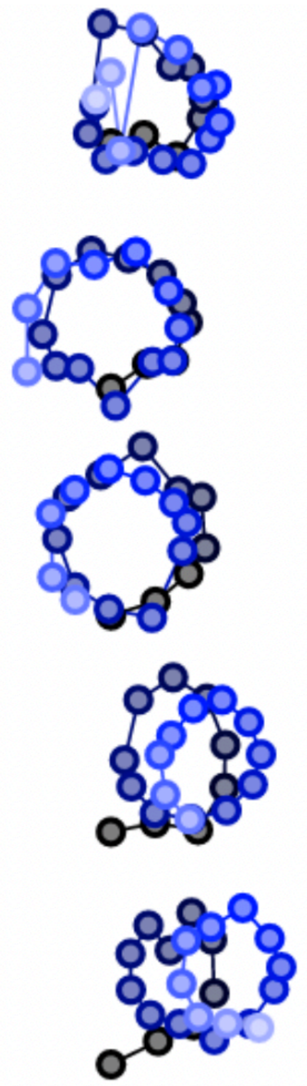
N. Goldman et al. PRX (2014); M. Bukov et al. Adv. in Phys. (2015); A. Eckardt, Rev. Mod. Phys. (2017)

Lattice 'cyclotron' orbits



Mean atom position during the evolution





Dy in synthetic dimensions!

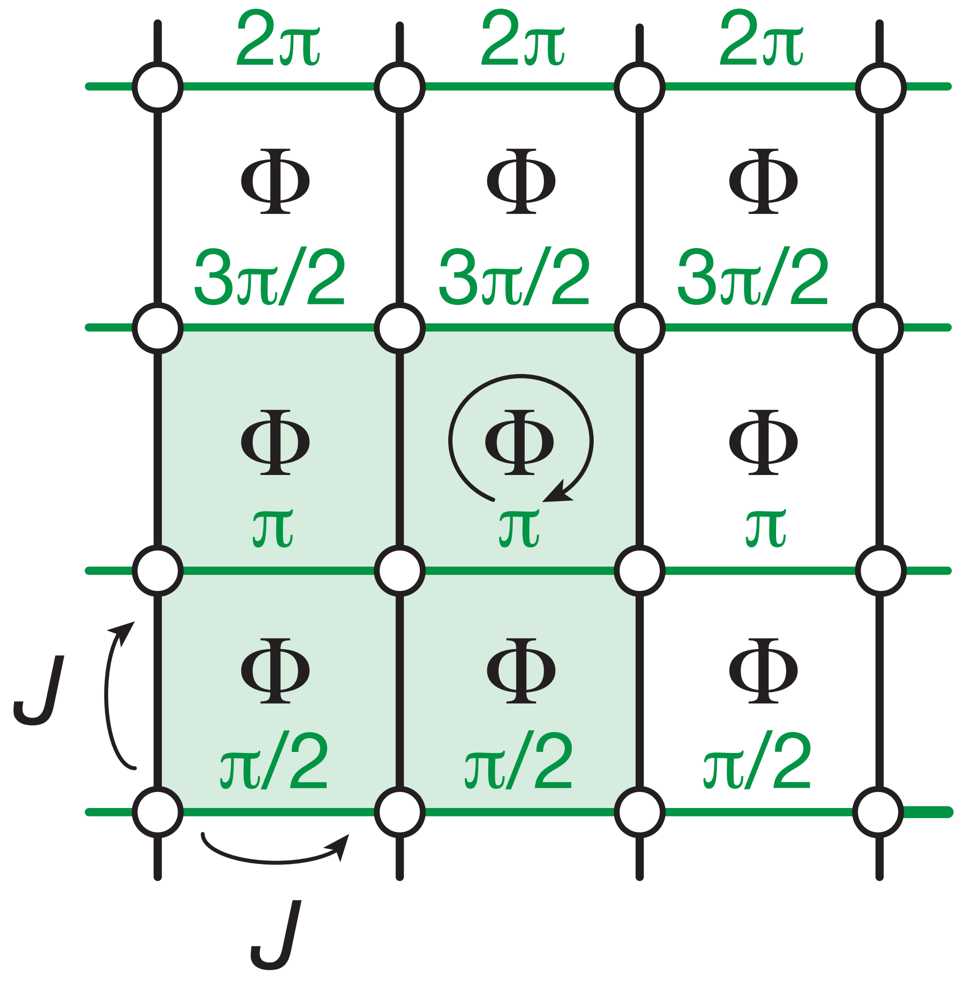
CHALOPIN, ..., NASCIMBENE, NAT. PHYS. (2020)

MA, ..., Bloch, Phys. Rev. Lett. **107**, 255301 (2011)

Topological lattice models

Hofstadter model

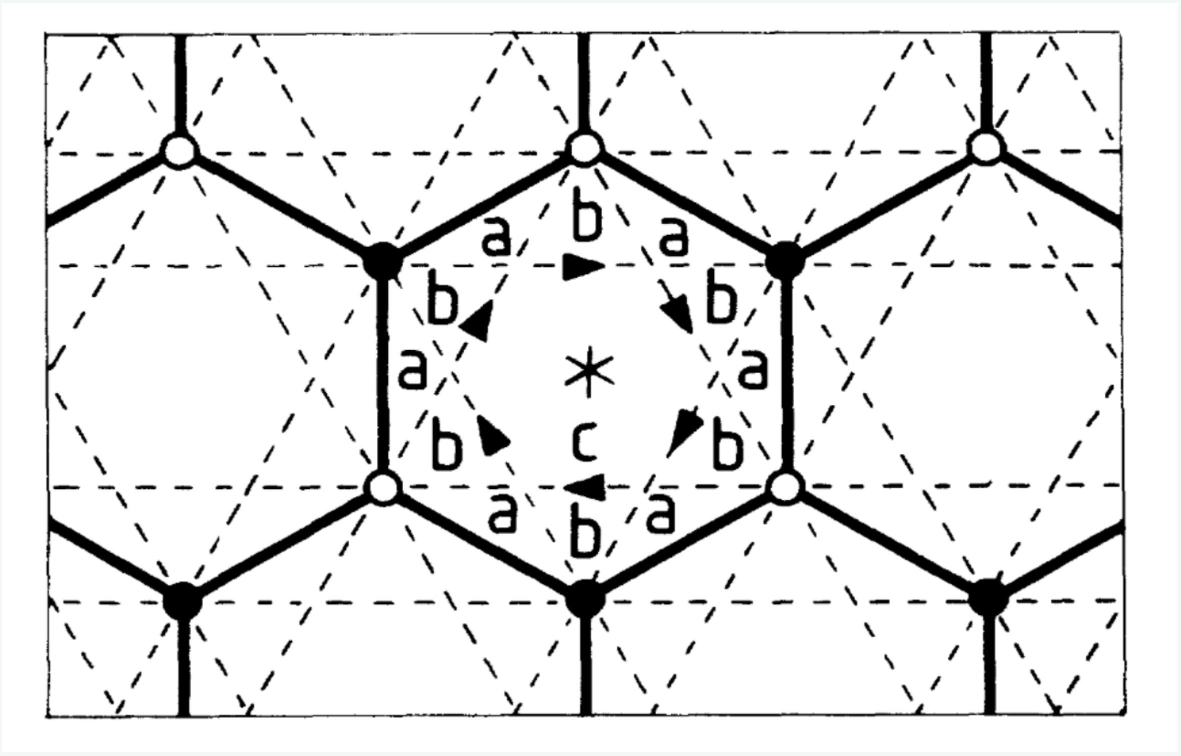
Harper, Proc. Phys. Soc., Sect.A **68**, 874 (1955)
Azbel, Zh. Eksp. Teor. Fiz. **46**, 929 (1964)
Hofstadter, PRB **14**, 2239 (1976)



$$\hat{H} = -J\sum_{m,n}\left(\mathrm{e}^{in\Phi}\hat{a}^\dagger_{m+1,n}\hat{a}_{m,n} + \hat{a}^\dagger_{m,n+1}\hat{a}_{m,n} + \mathrm{h.c.}\right)$$

Haldane model

Haldane, PRL **61**, 2015 (1988)



$$\hat{H} = \sum_{\langle ij\rangle} t_{ij}\hat{c}^\dagger_i\hat{c}_j + \sum_{\langle\langle ij\rangle\rangle} \mathrm{e}^{i\Phi_{ij}} t'_{ij}\hat{c}^\dagger_i\hat{c}_j + \Delta_{AB}\sum_{i\in A}\hat{c}^\dagger_i\hat{c}_i$$

Ma et al., PRL (2013); H. Miyake et al., PRL (2013)
E. M. Tai et al., Nature (2017)
G. Jotzu et al., Nature (2014) ;Tarnowski et al., Nat. Comm. (2019)

Review: N. Cooper et al. Rev. Mod. Phys. **91**, 015005 (2019)

Topological invariants

Chern number:

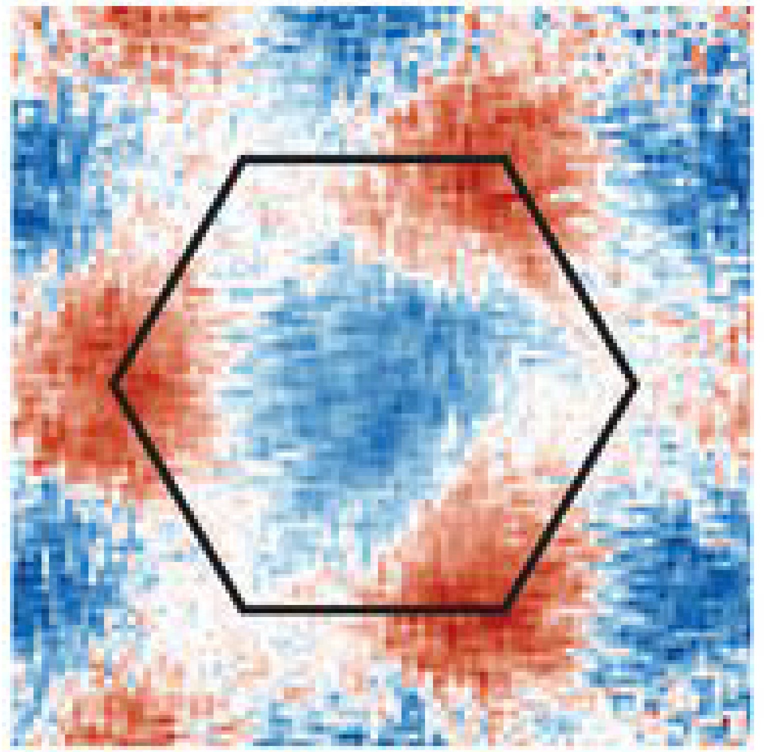
$$\mathcal{C}^\mu = \frac{1}{2\pi}\int_{\mathrm{BZ}} \Omega^\mu \mathrm{d}^2 q$$

$|u_\mu(\mathbf{q})\rangle$: periodic Bloch function

μ: band index

Berry curvature:

$$\Omega_\mu = i\left(\langle \partial_{q_x} u_\mu | \partial_{q_y} u_\mu \rangle - \langle \partial_{q_y} u_\mu | \partial_{q_x} u_\mu \rangle\right)$$

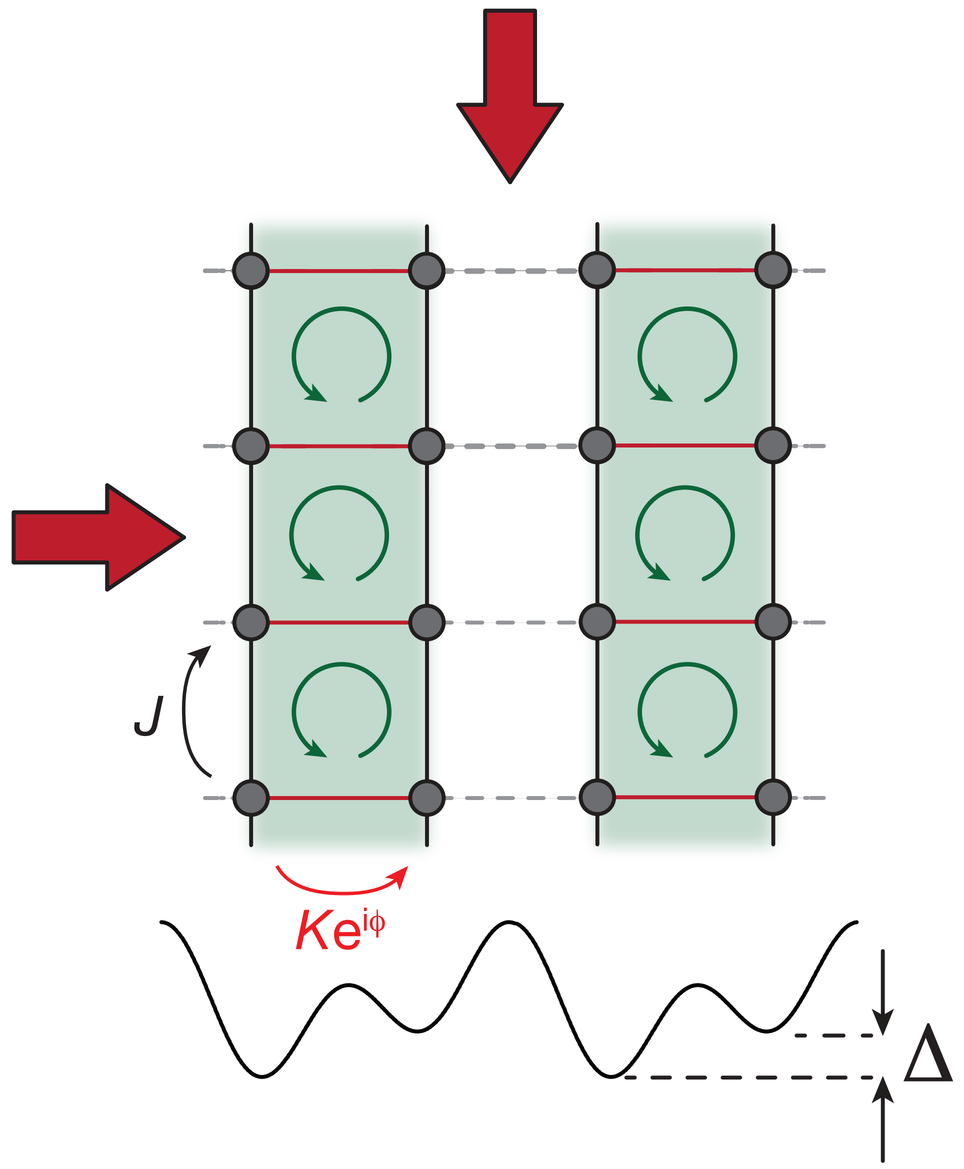


Weitenberg/Sengstock

M. Atala, et al., Nat. Phys. (2013); L. Duca et al., Science (2015)
G. Jotzu et al., Nature (2014); M. A. et al., Nature Phys. (2015)
N. Fläschner, Science (2016); T. Li, Science (2016)
Tarnowski et al., Nat. Comm. (2019);
L. Asteria et al., Nat. Phys. (2019);
B. Rem et al., Nat. Phys. (2019); .....

(selected) experimental results

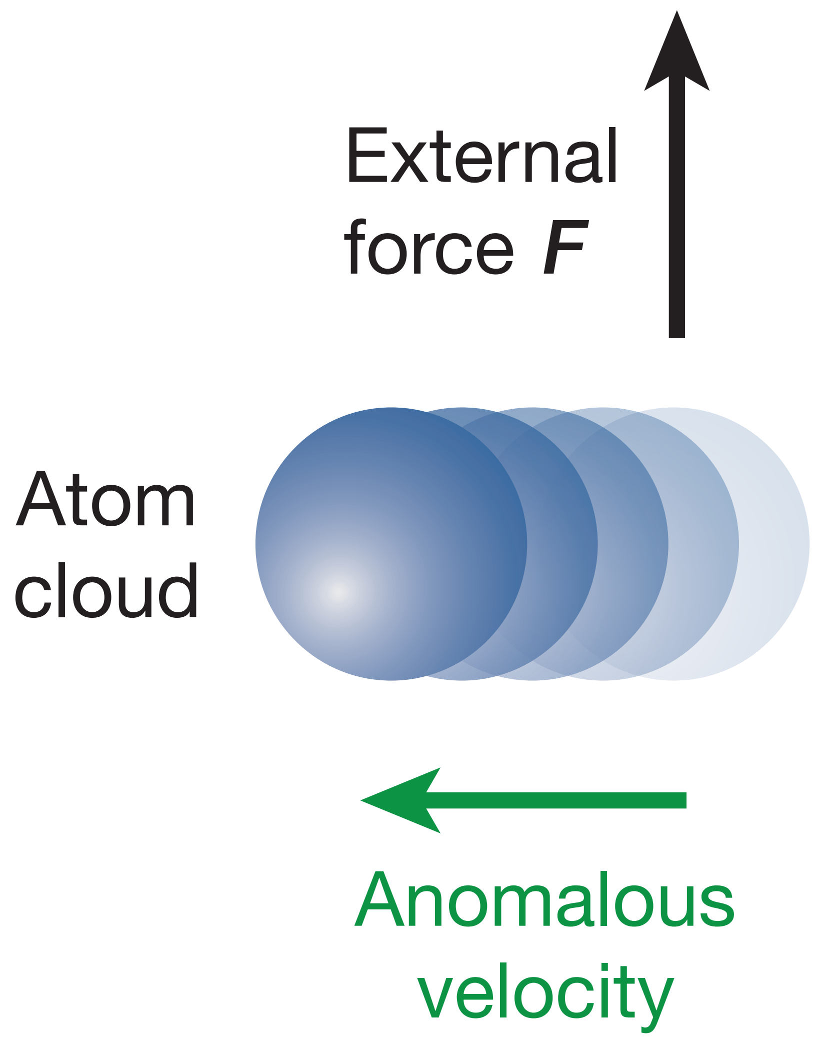
Bosonic flux ladders



Observation of chiral Meissner-like currents

Atala, MA, ..., Bloch, Nat. Phys. (2014)

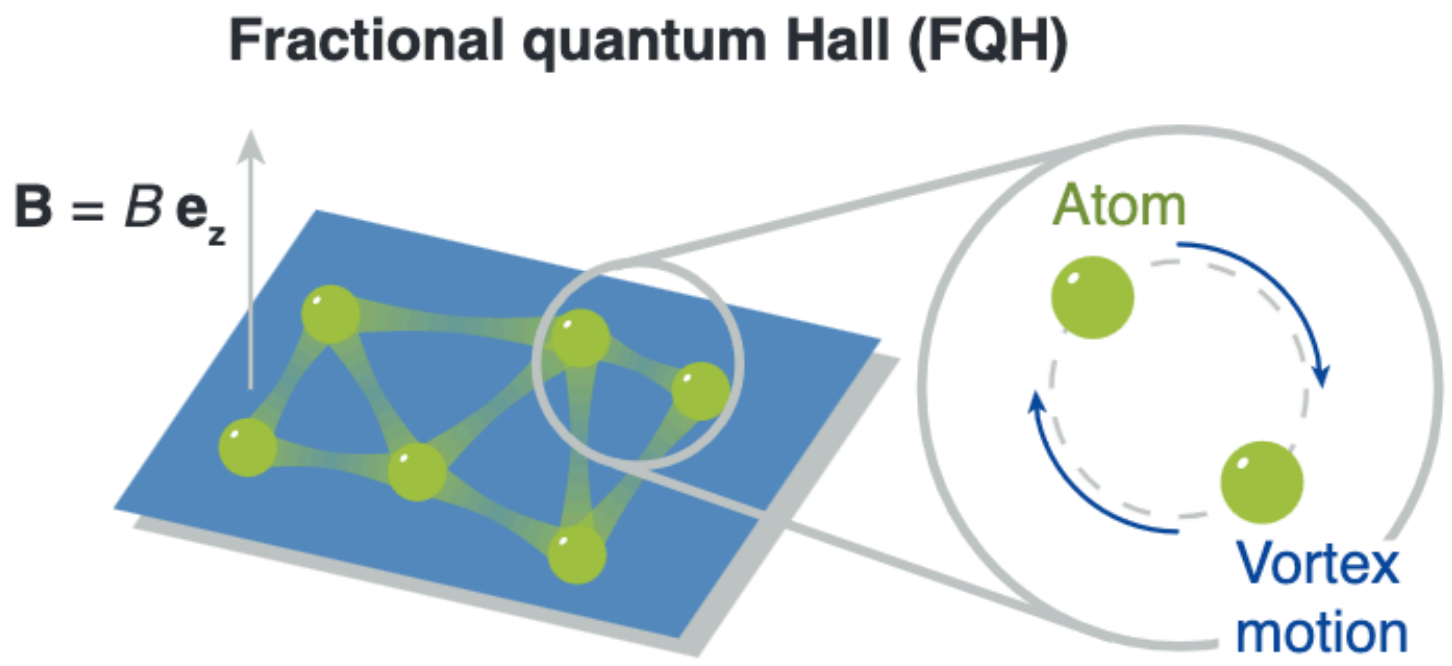
Hall deflection



Chern-number measurement with bosonic atoms

MA, ..., Bloch, Nat. Phys. (2015)

2-particle Laughlin state



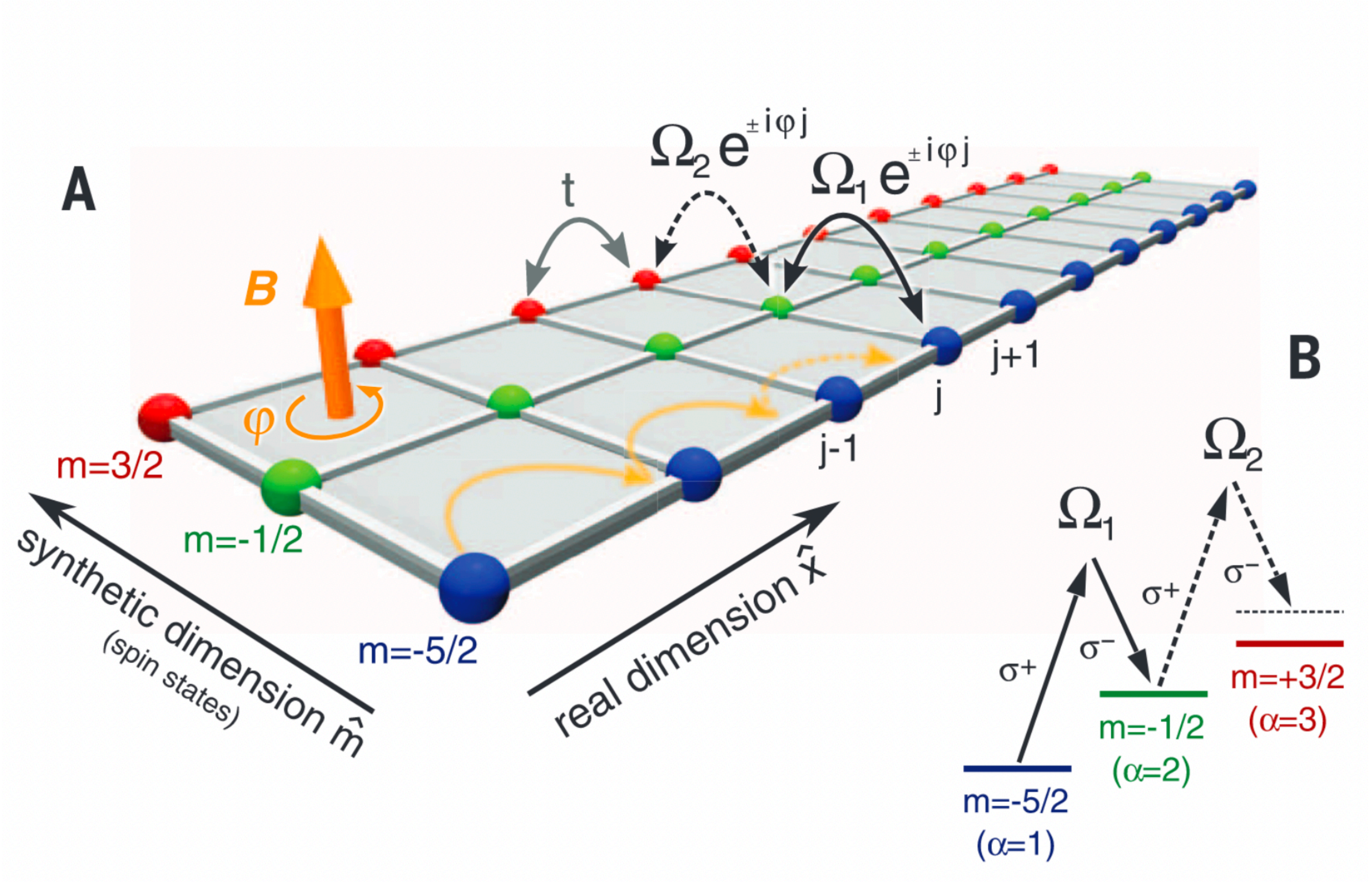
Towards fractional quantum Hall physics

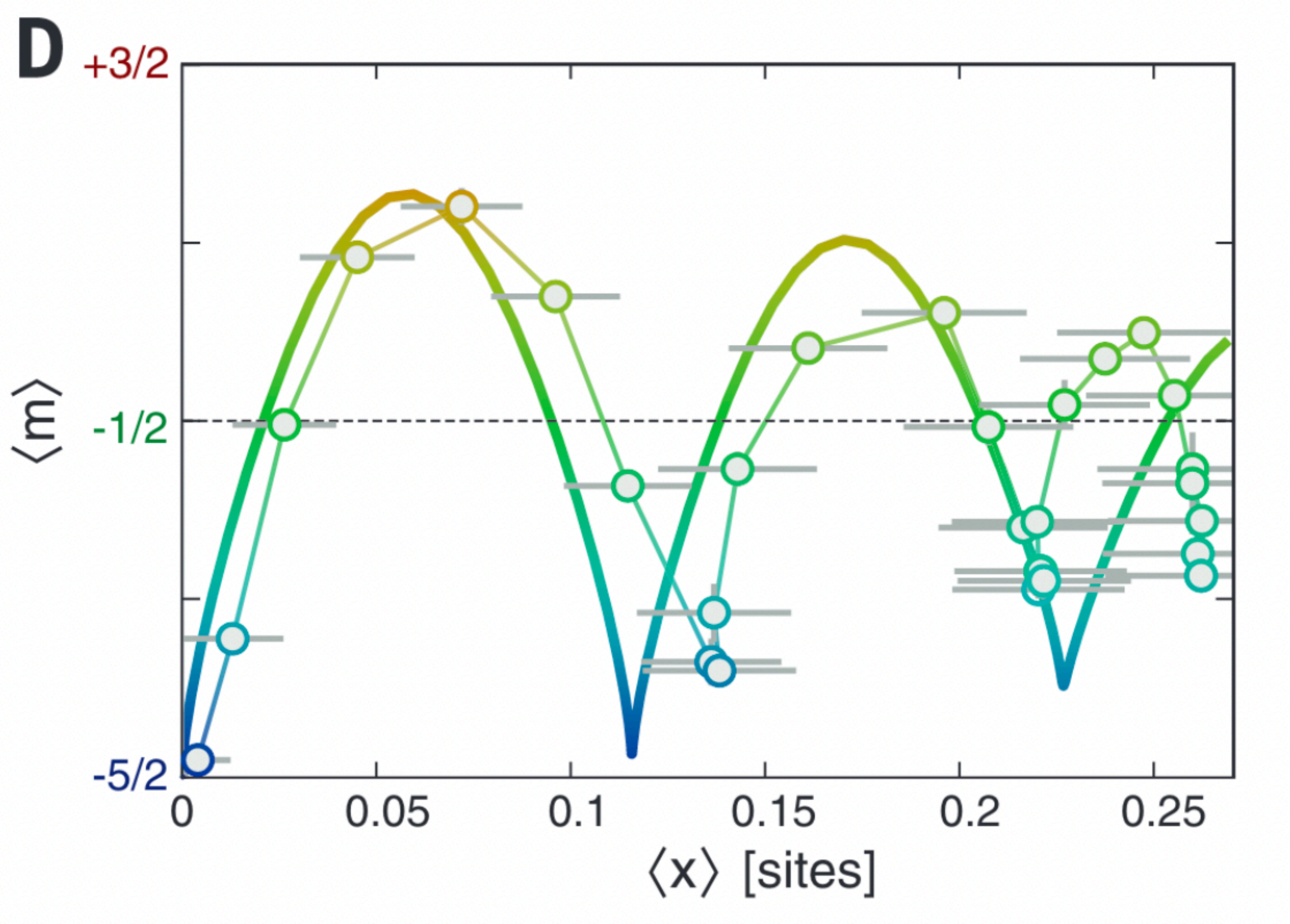
Léonard, ..., Greiner, arXiv:2210.10919

REVIEWS: N. COOPER ET AL. REV. MOD. PHYS. **91**, 015005 (2019); MA ET AL. C. R. PHYSIQUE **19**, 394-432 (2018),

How to generate topological edge modes?

Synthetic dimensions



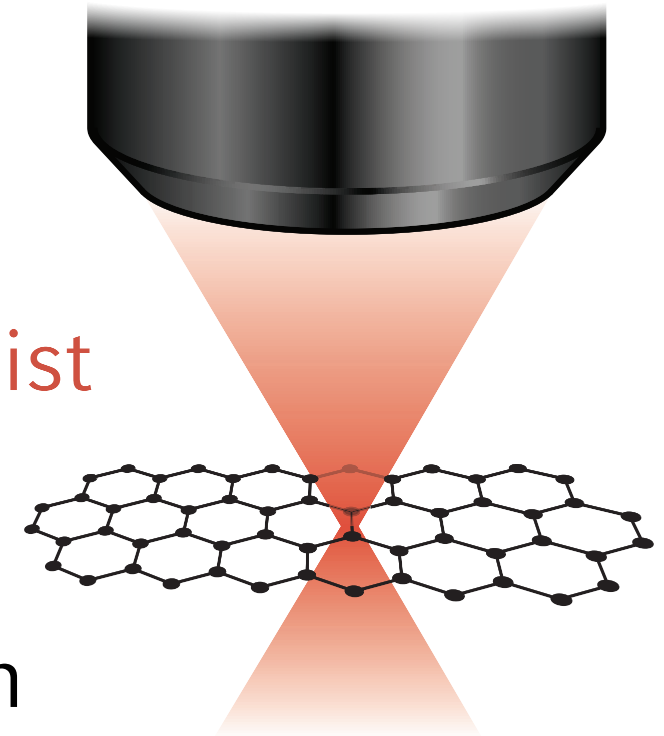


Mancini, ..., Fallani, Science **349** (2015)
Stuhl, ..., Spielman, Science **349** (2015)

See also: Chalopin, ..., Nascimbène, Nature Physics (2020)

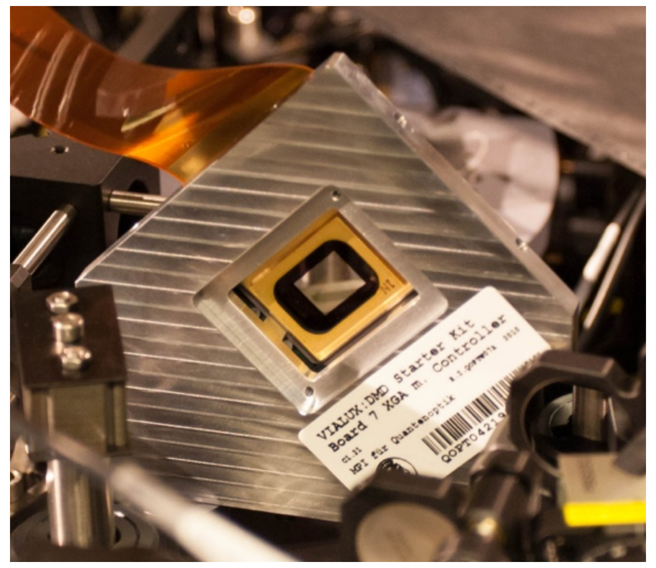
Edge dynamics

Realizing a sharp edge:



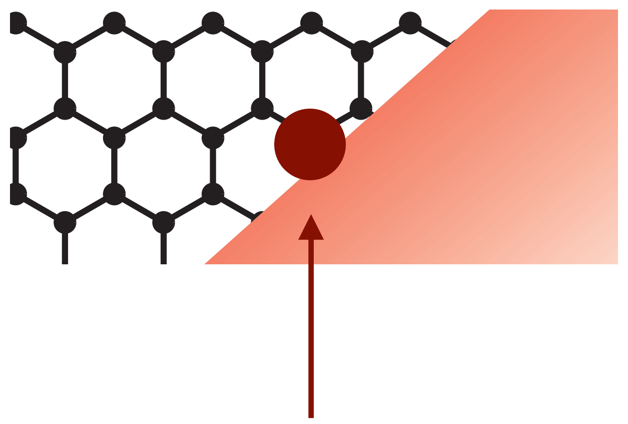
+

DMD



638nm light (repulsive)

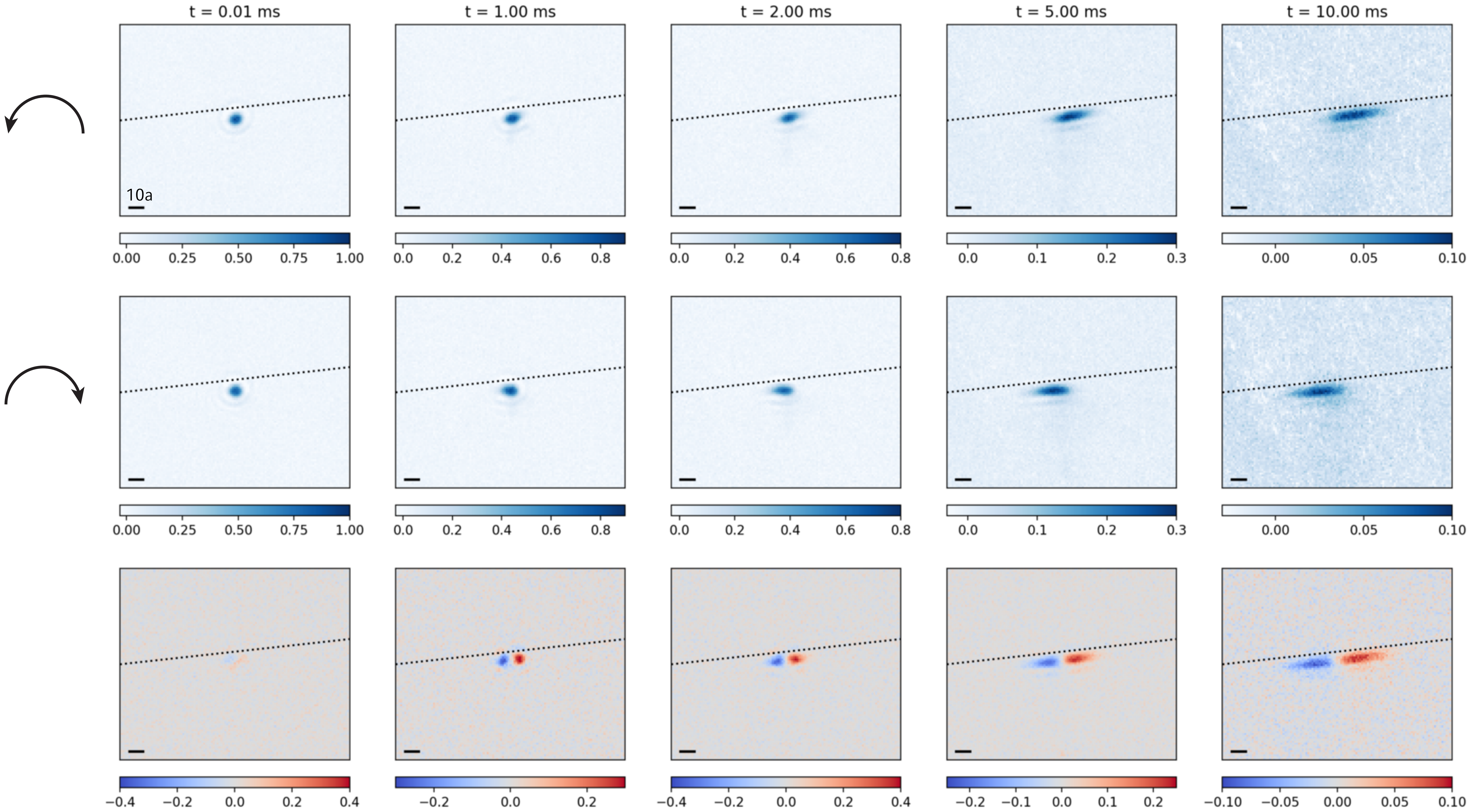
=



Width of the edge: 2-3 lattice sites!

Preliminary!

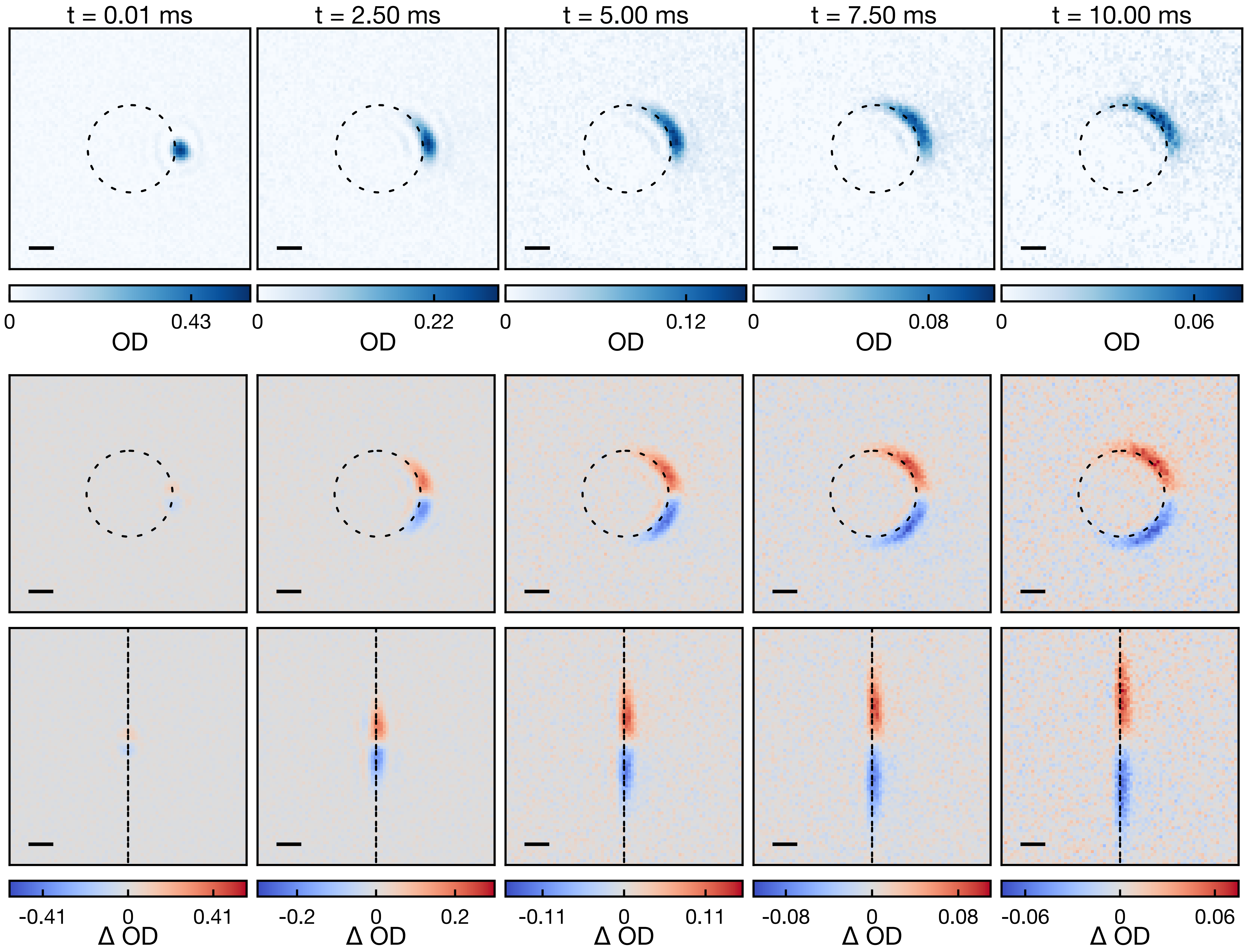
Edge dynamics in anomalous regime



f=7kHz, m=0.25

Preliminary!

Edge dynamics in anomalous regime



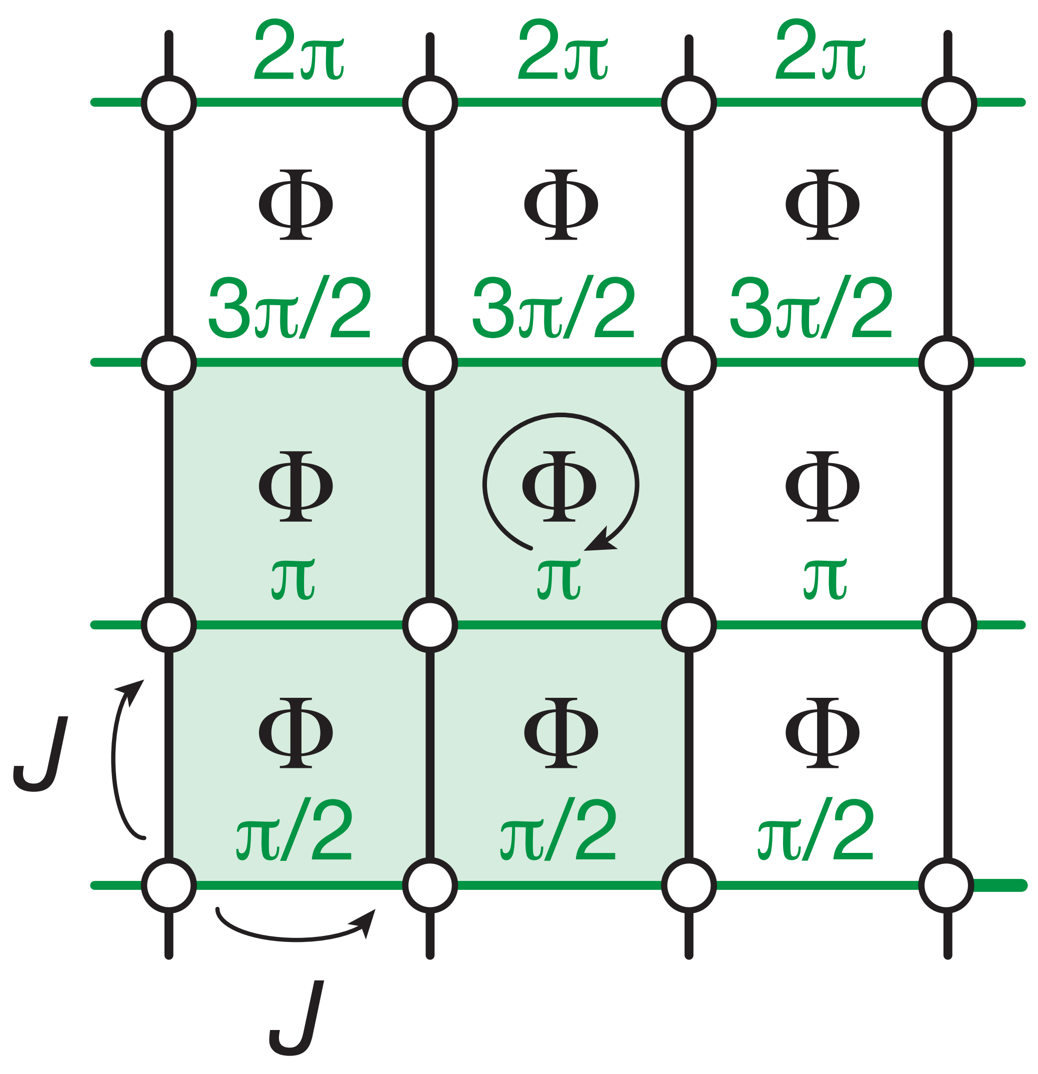
f=7kHz, m=0.25

Preliminary!

Application:
Quantum Simulation of
gauge theories

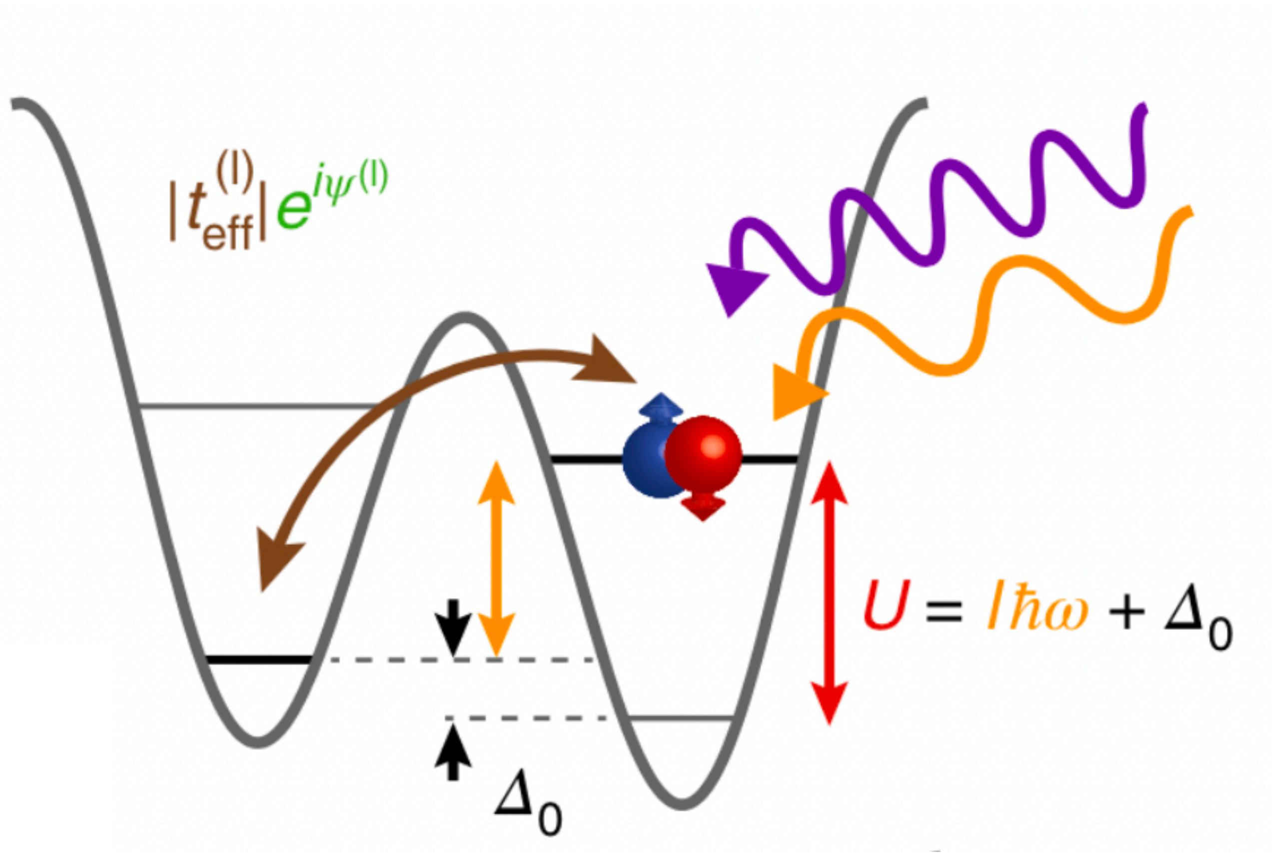
Engineering novel Hamiltonians

Topological phases / artificial magnetic fields:



Hofstadter/Haldane model

Density-dependent gauge fields:



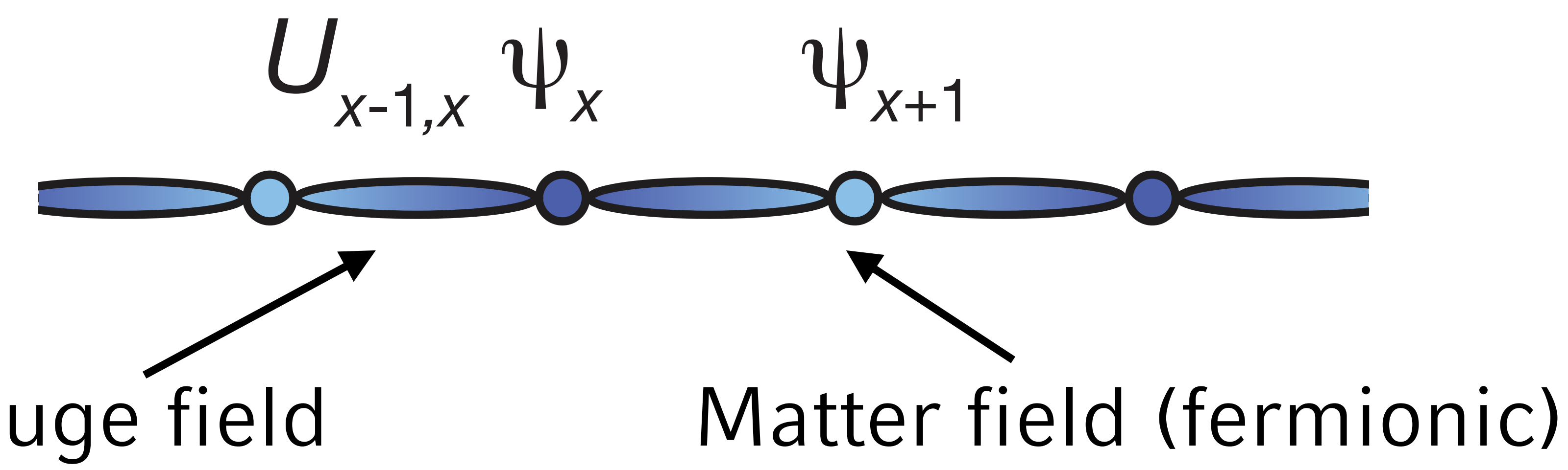
Engineered field depends on site occupation

But: No Gauss's law!

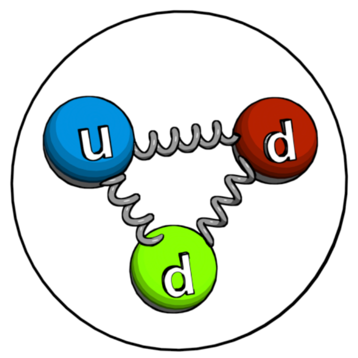
ZURICH, HARVARD, MIT, HAMBURG, NIST, LENS, CHICAGO, ...

Gauge theories

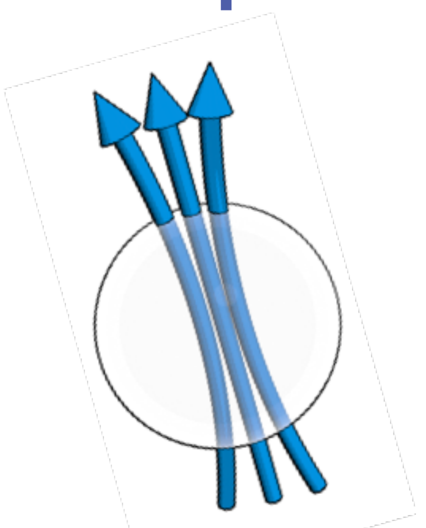
Lattice gauge theories:



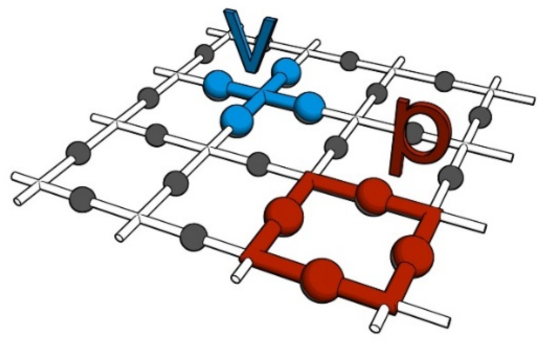
K. G. Wilson



High Energy Physics



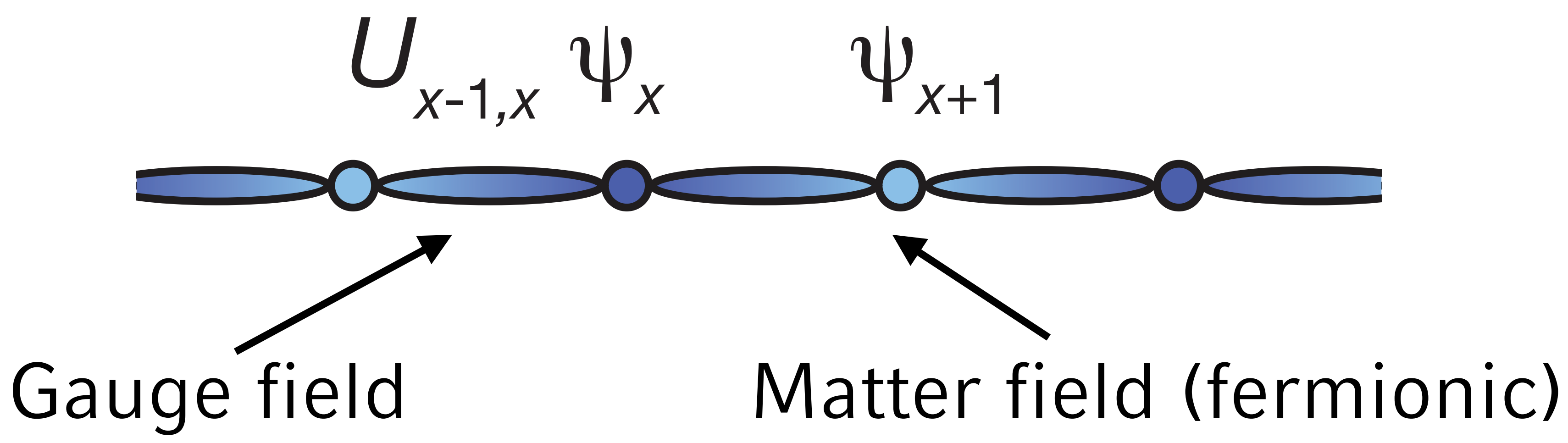
Condensed Matter Physics



Top. Quantum Computation

Gauge theories

Lattice gauge theories:



K. G. Wilson

Challenges for Quantum simulation:

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

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

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)

U(1) lattice gauge theory in 1D

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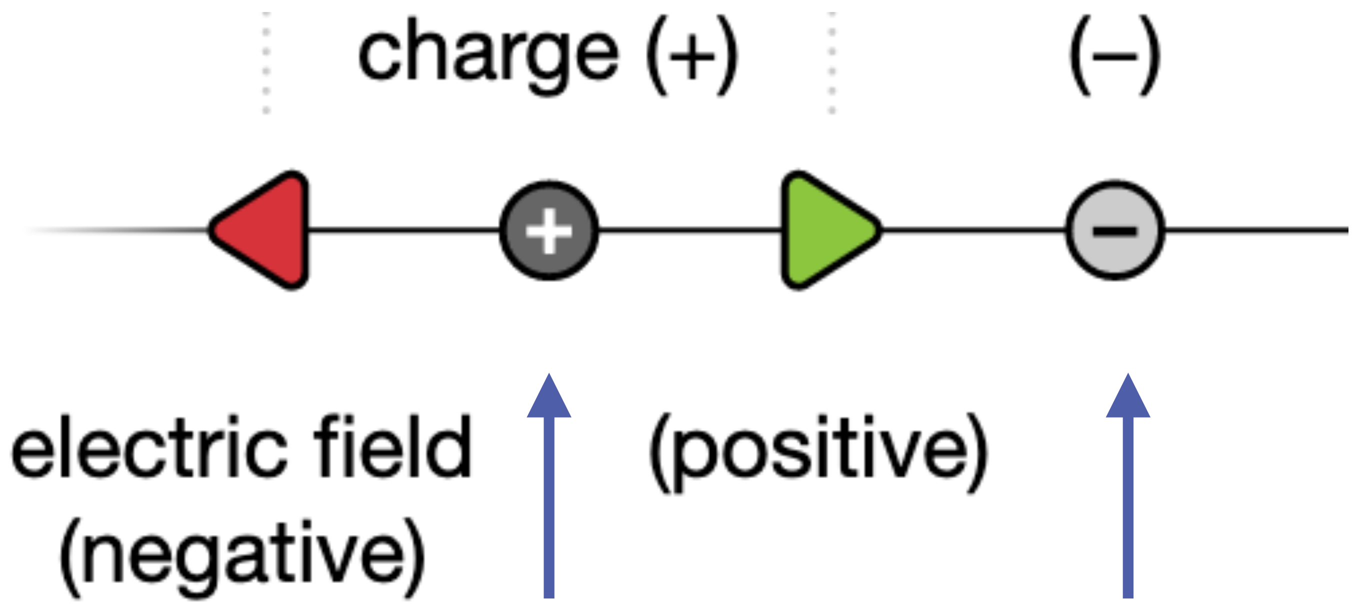
Local charge:

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



even
occupied

odd
empty

Kogut & Susskind, PRD 11, 395 (1975)

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

U(1) lattice gauge theory in 1D

Quantum electrodynamics in 1D
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Local charge:

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

Gauss's law:

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

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

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

U(1) lattice gauge theory in 1D

Quantum electrodynamics in 1D

lattice Schwinger model

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

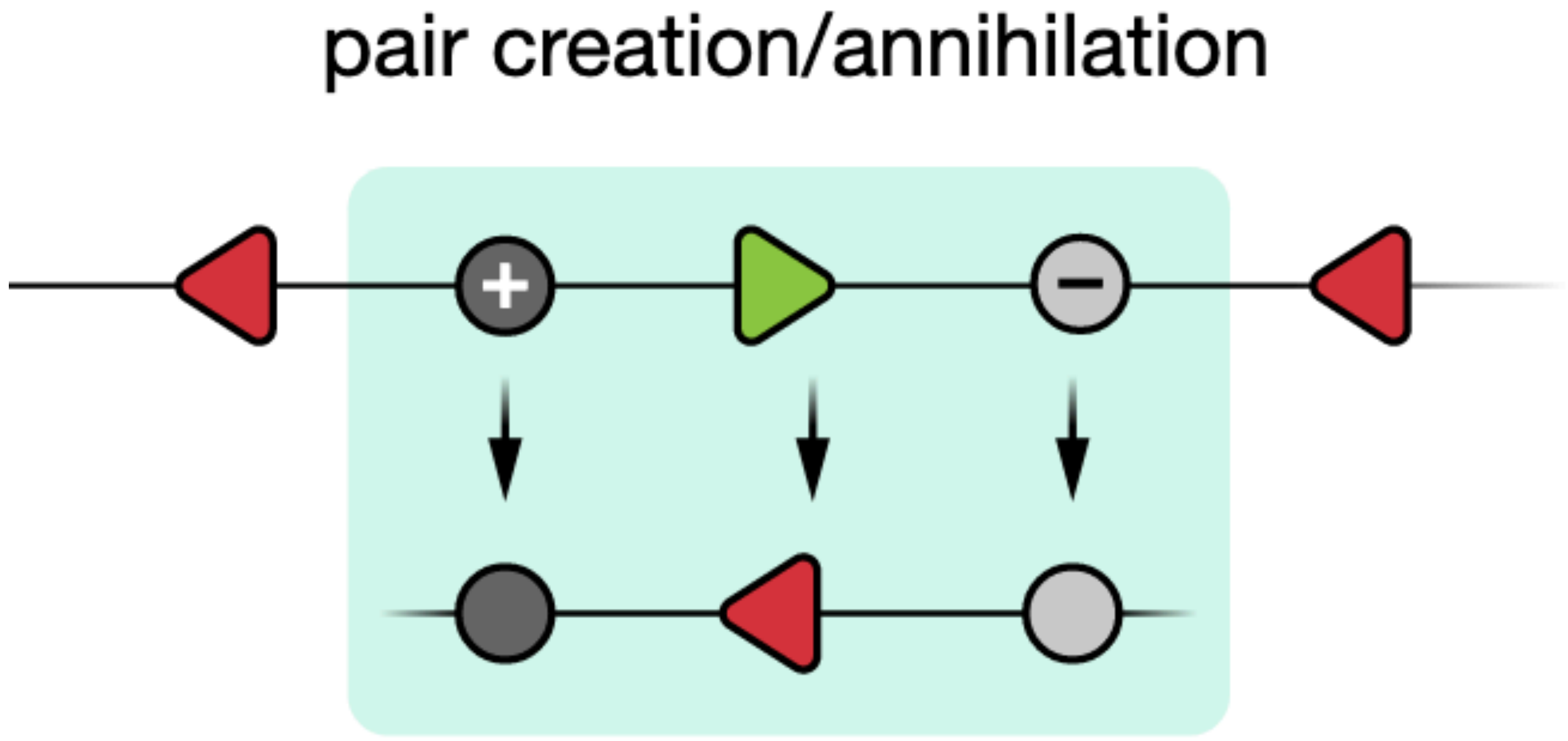
$$E_{j,j+1} \rightarrow S^z$$
$$U_{j,j+1} \rightarrow S^+$$

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:



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

$$E_{j,j+1} \to S^z$$
$$U_{j,j+1} \to S^+$$

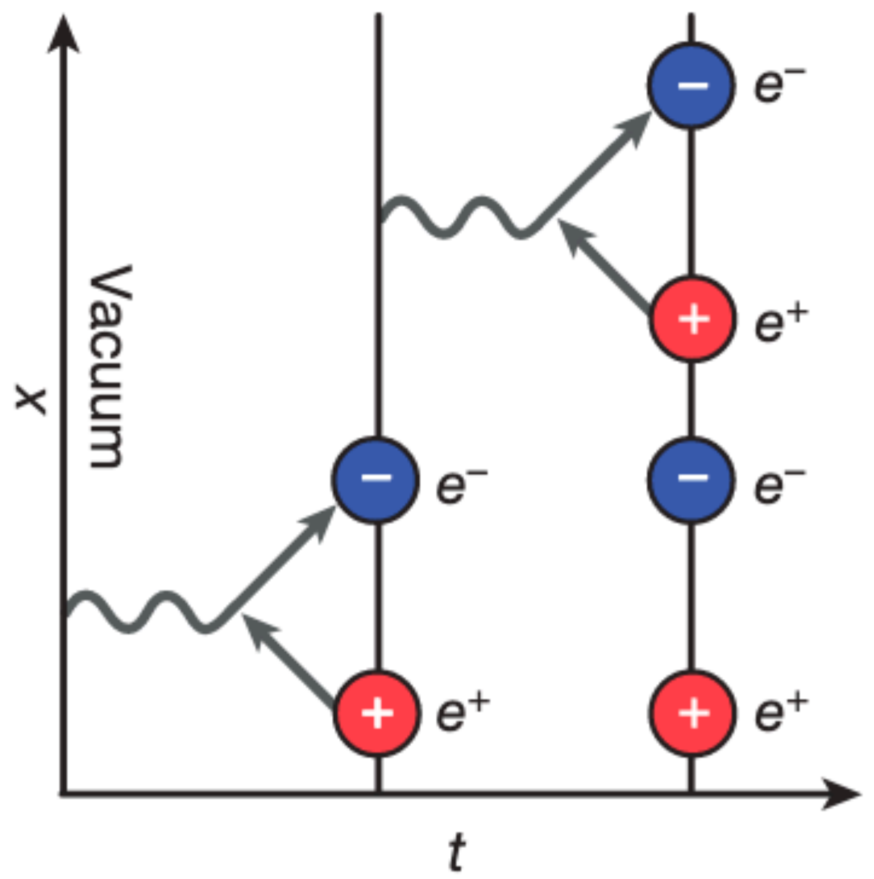
reduced Hilbert-space for link operators

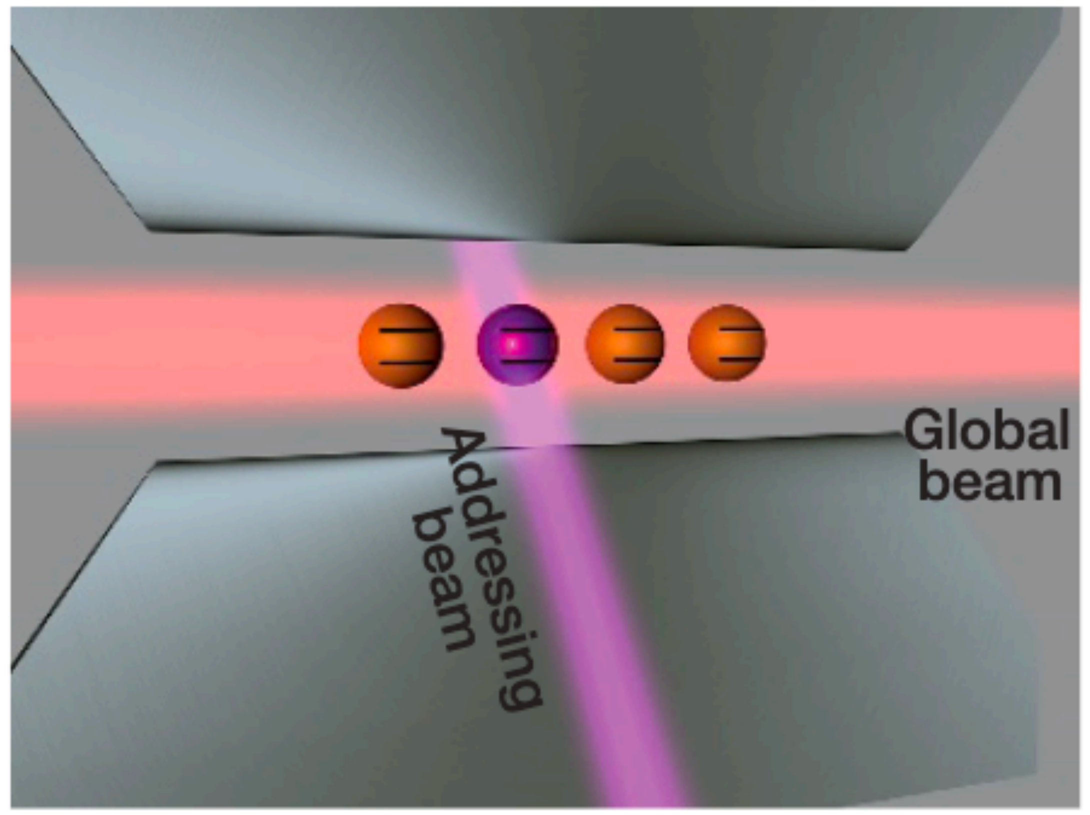
KOGUT & SUSSKIND, PRD 11, 395 (1975)
CHANDRASEKHARAN & WIESE, NUCL. PHYS. B 492, 455 (1997)

State-of-the-art

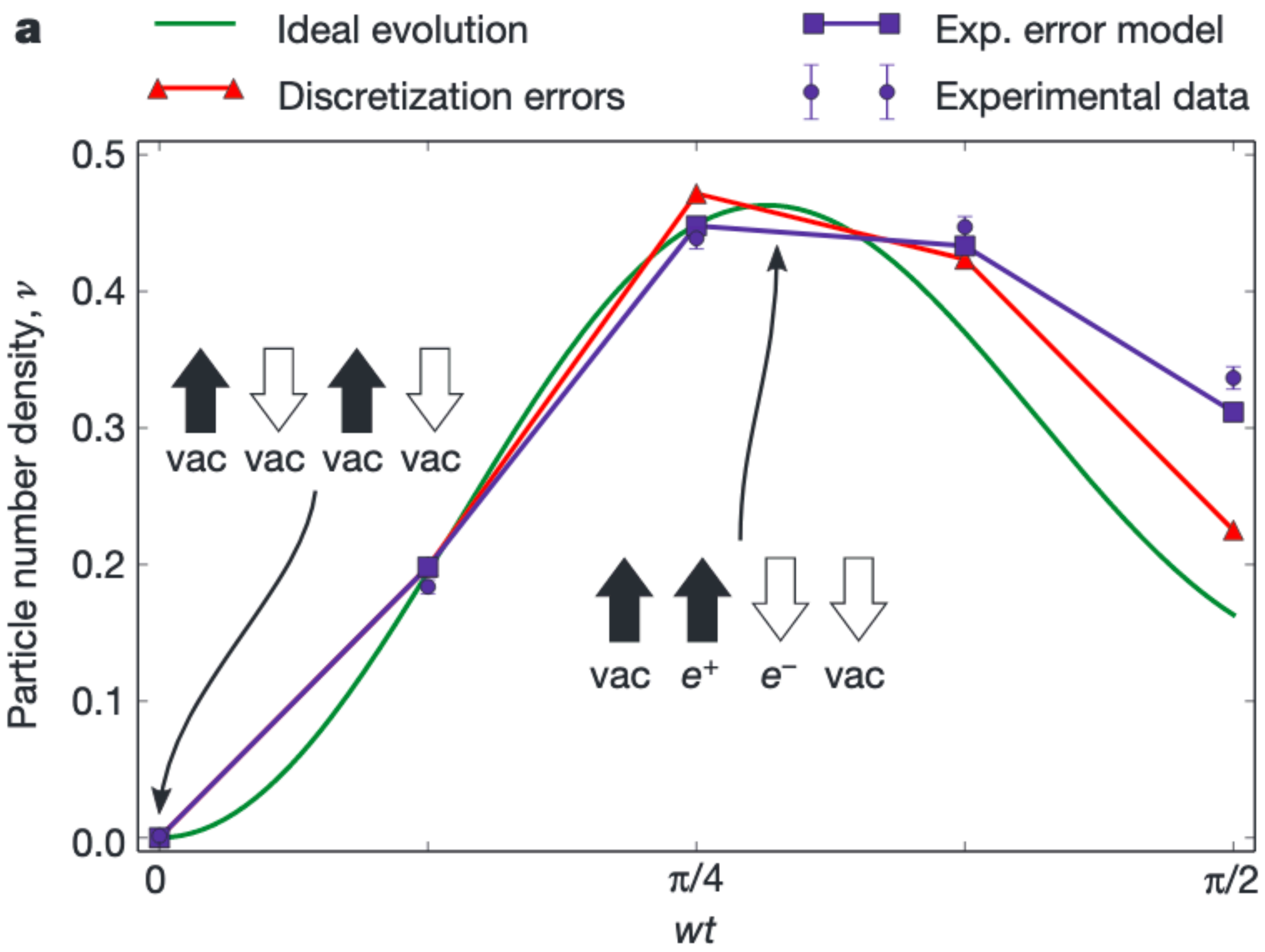
Few-ion quantum simulation

particle-antiparticle creation processes





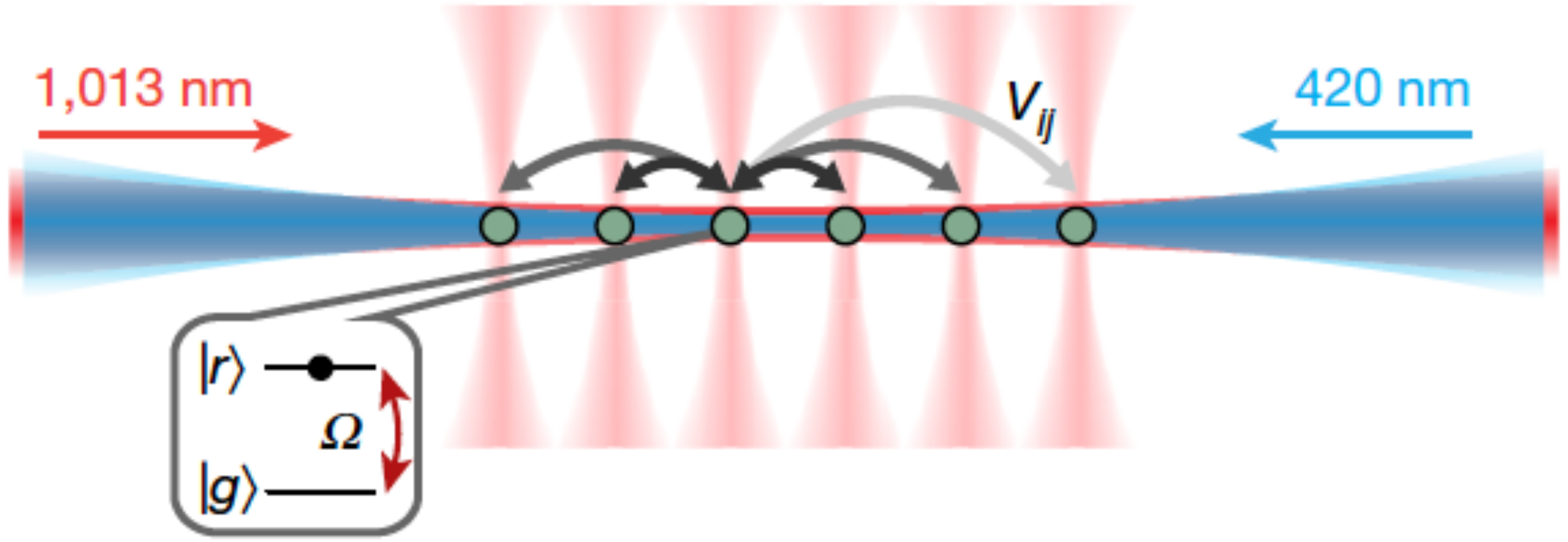
E. A. Martinez et al. Nature **534**, 516-519 (2016);
N. H. Nguyen et al. PRX Quantum **3**, 020324 (2022)



Gauge-fields are eliminated ↔ exotic long-range interactions

State-of-the-art

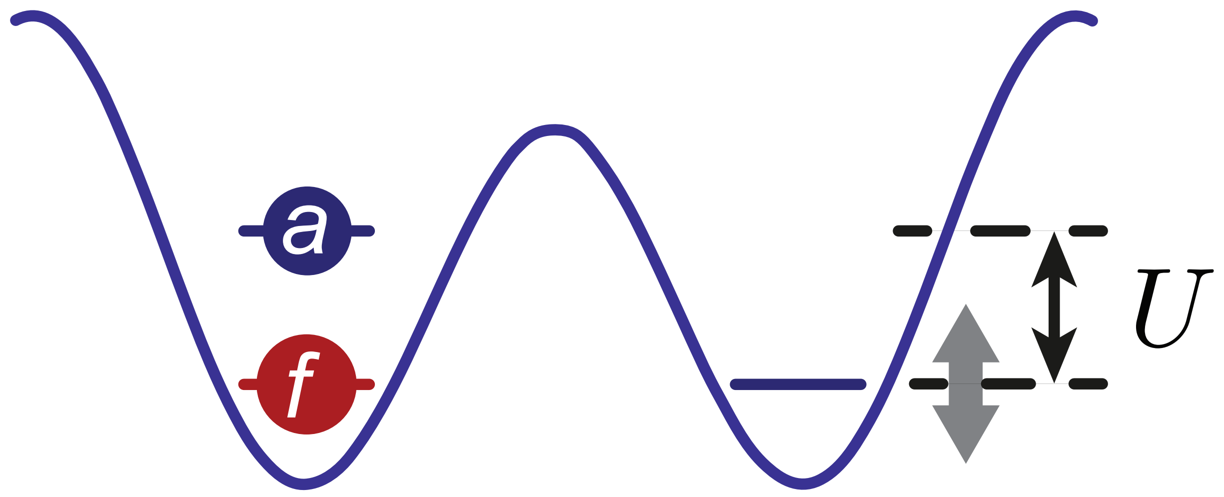
Rydberg atom arrays



H. Bernien et al. Nature **551**, 579 (2017);
F. M. Surace et al. Phys. Rev. X **10**, 021041 (2020)

Matter-fields are eliminated

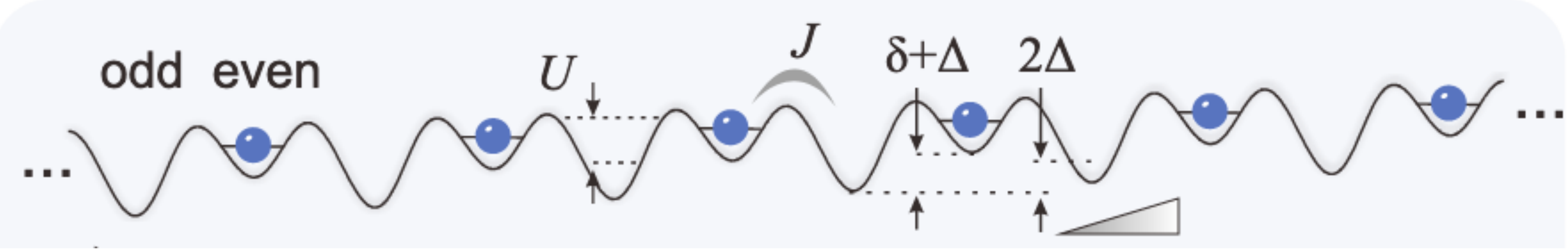
Building block



Z2 LGT:
C. Schweizer,..., MA, Nat. Phys. **15**, 1168-1173 (2019)

U(1) LGT:
A. Mil et al. Science **367**, 1128-1130 (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., arXiv:2210.17032 (2022)

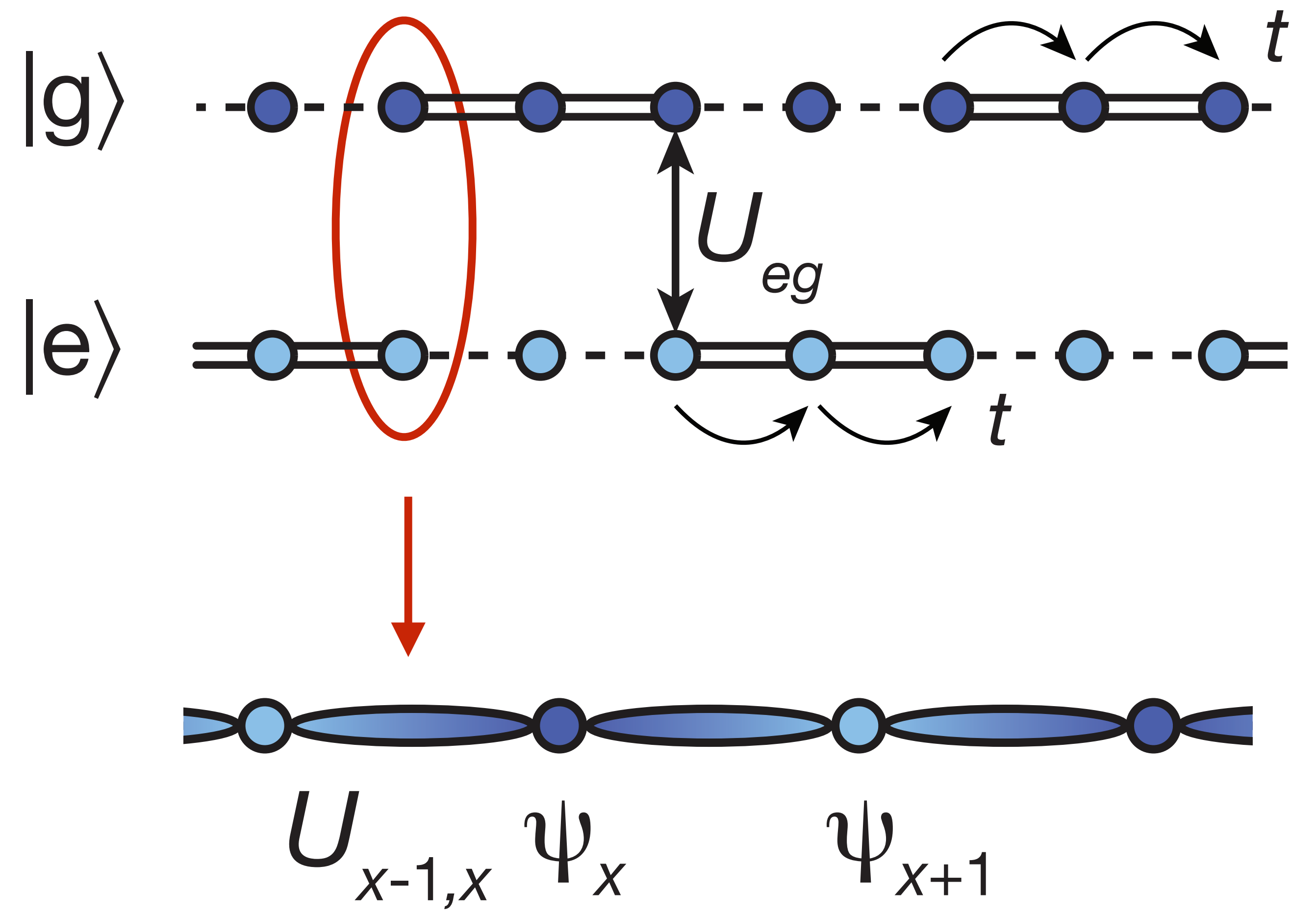
Our goal:

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

Proposed experimental scheme

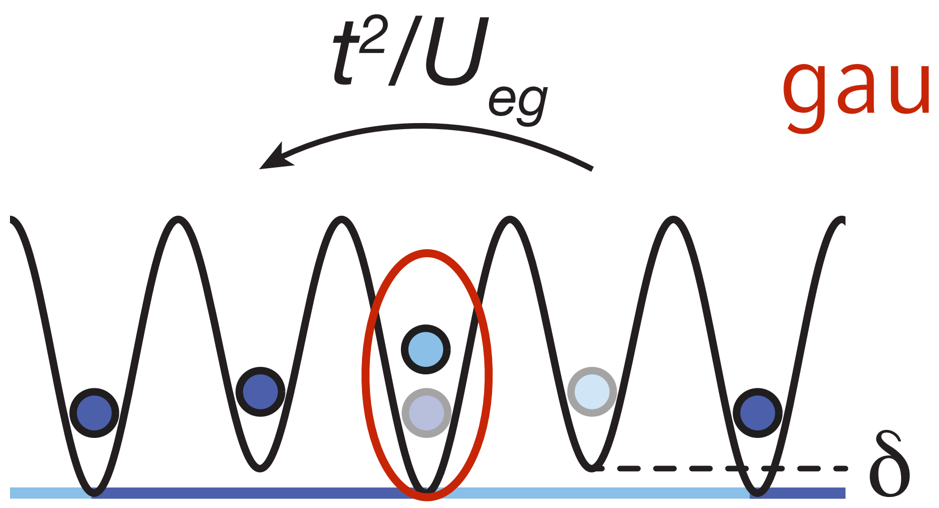
The scheme

- State-dependent triple-well lattice



S=1/2 quantum link model

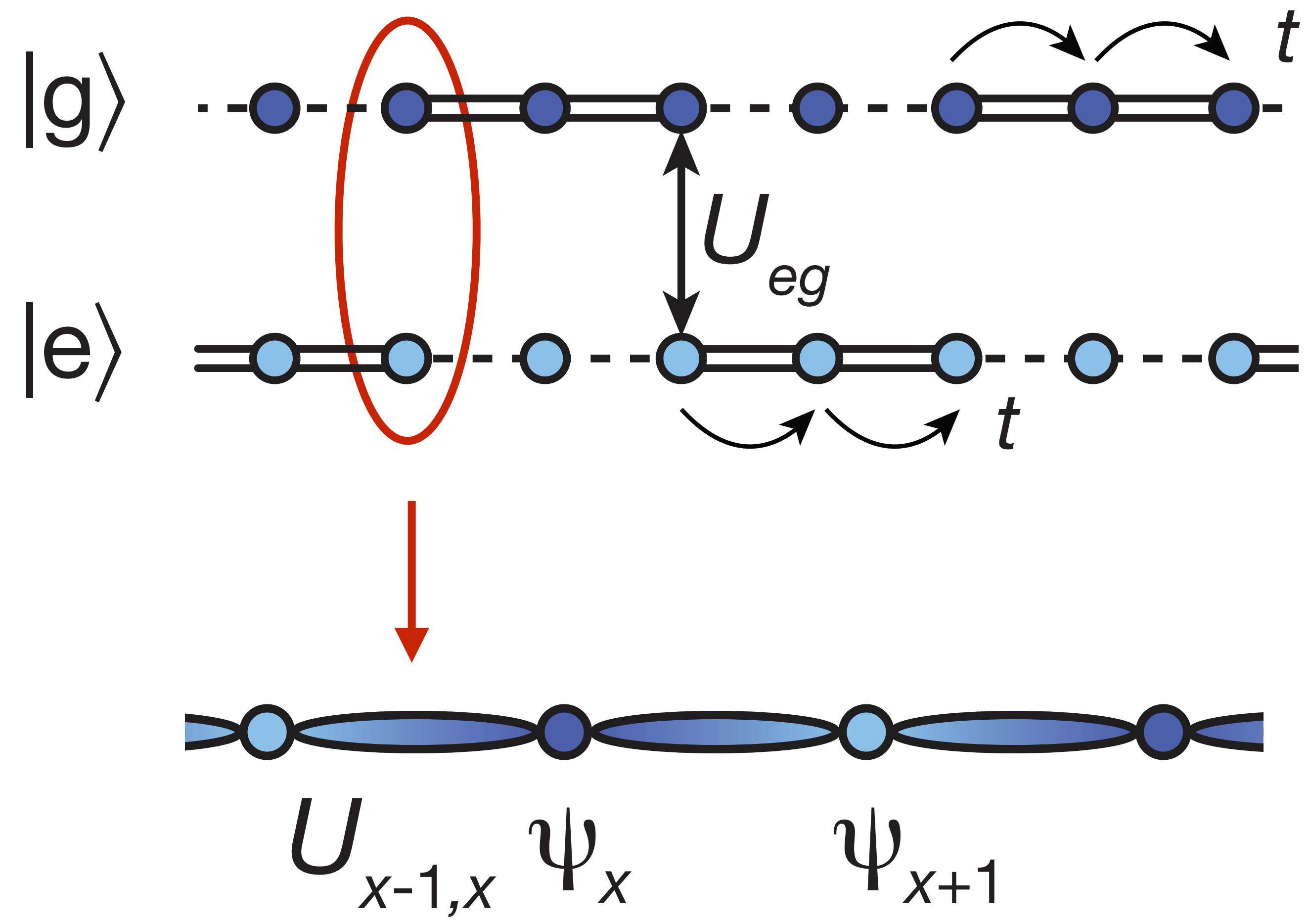
- *Building block:* correlated hopping of fermions



gauge field

The scheme

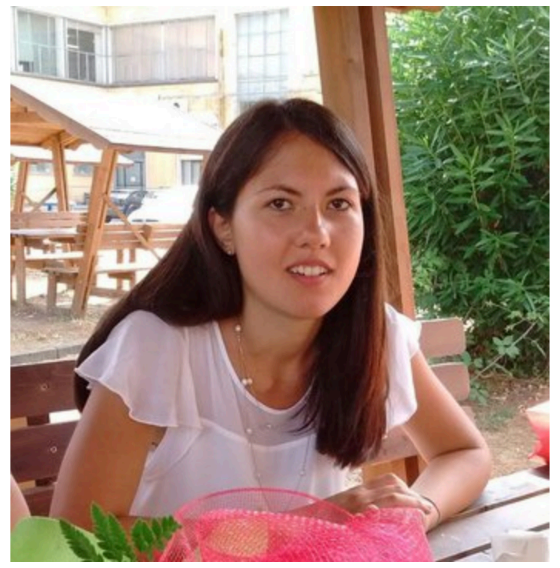
- State-dependent triple-well lattice



S=1/2 quantum link model

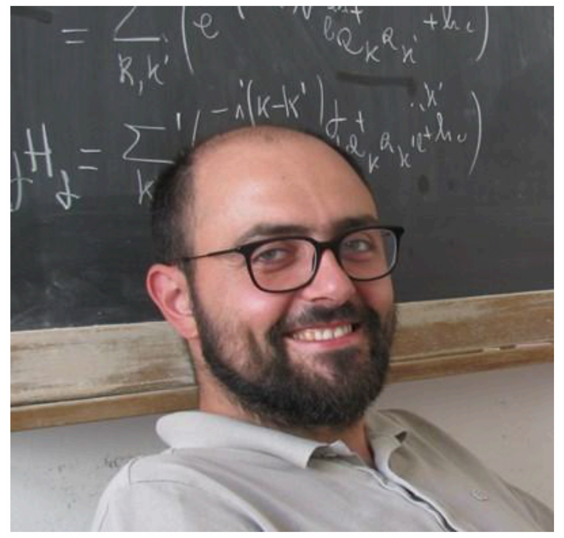
- **Ab initio calculations:**

N. Darwah Oppong



F. Surace

P. Fromholz



M. Dalmonte

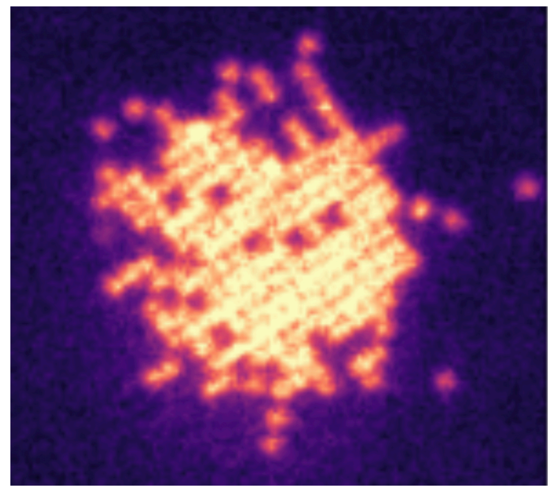
F. M. Surace, P. Promholz, N. Darkwah Oppong, M. Dalmonte, MA, arXiv:2301.03474

Experimental platform & current status

Novel hybrid tweezer-lattice platform

Optical lattices:

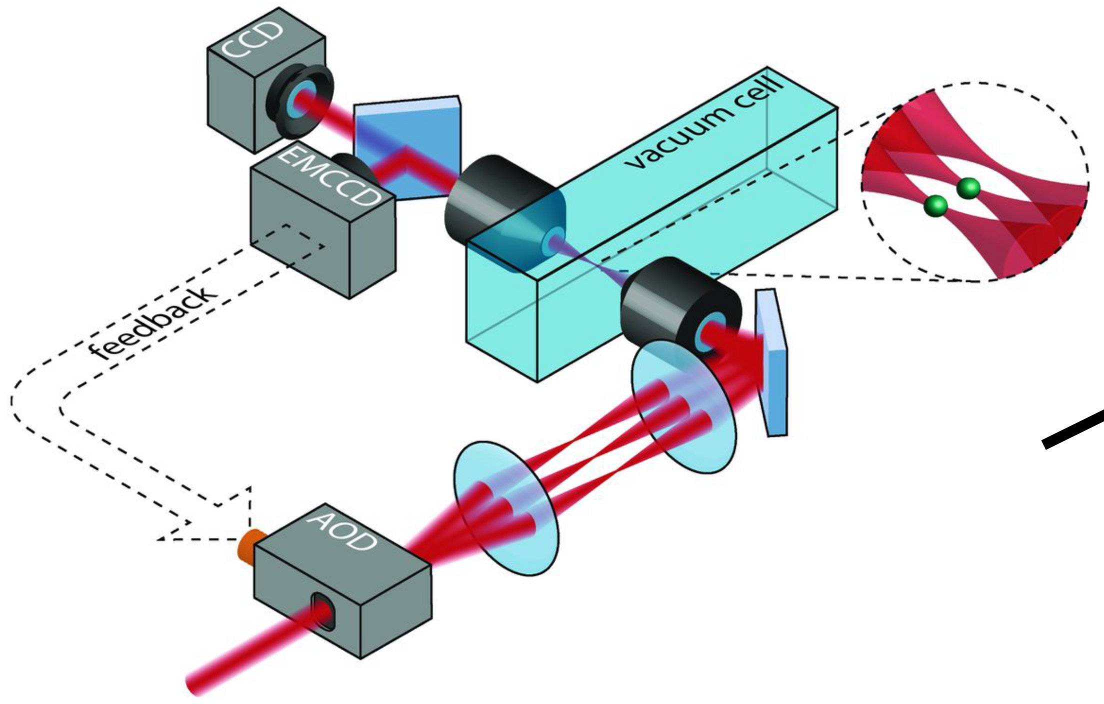
large-scale systems,
defect free



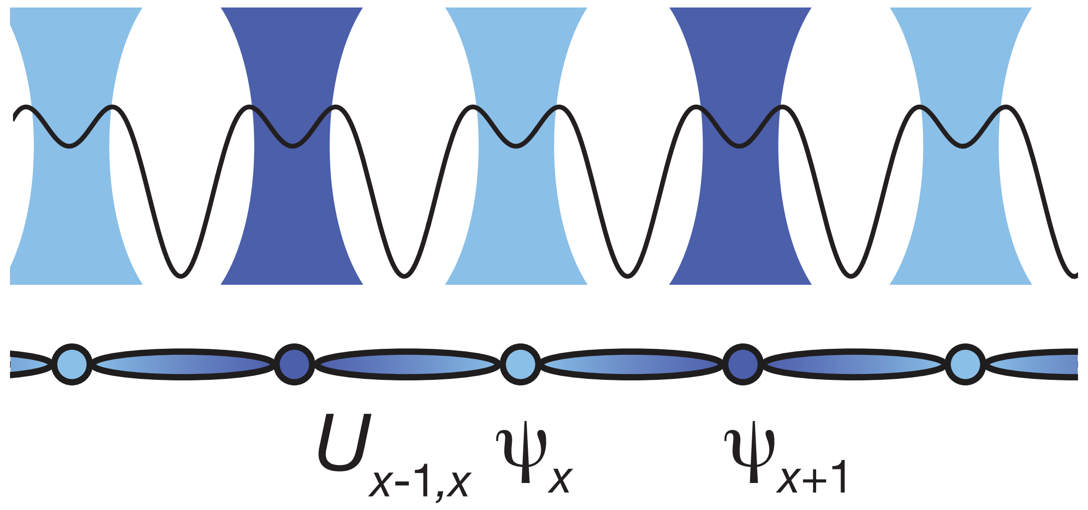
Optical tweezers:

local dynamical
control

M. Endres, Science (2016)
D. Barredo, Science (2016)



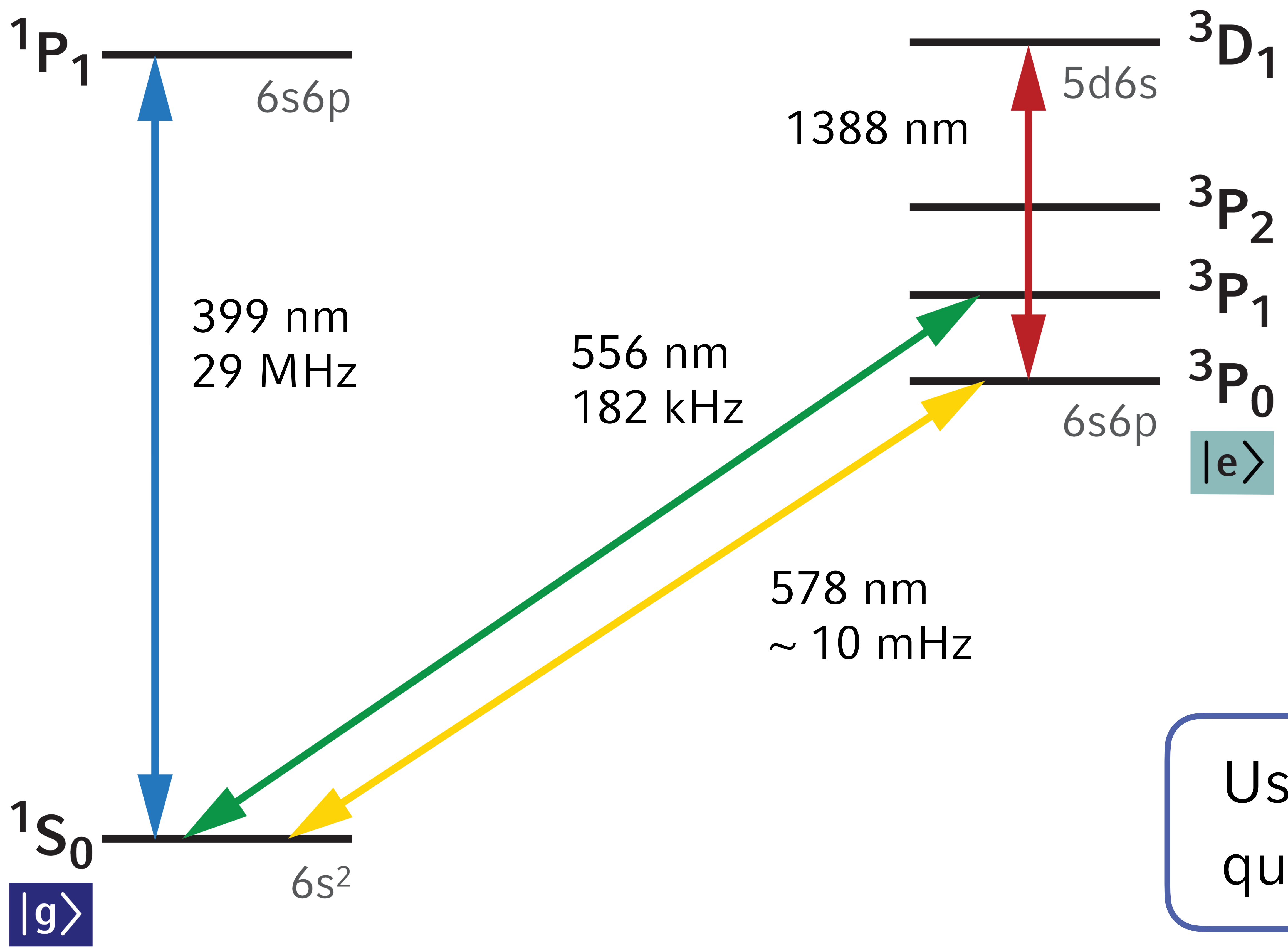
Local state-dependent control of tunneling



Implementation

ground- and excited clock state of Yb

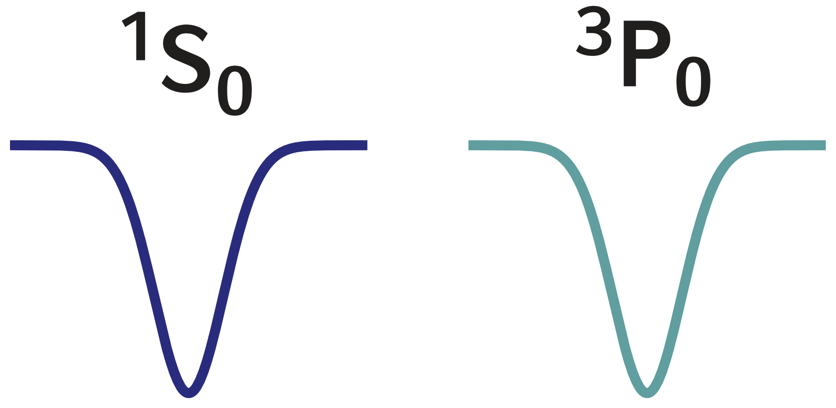
Why Alkaline-earth(-like) atoms

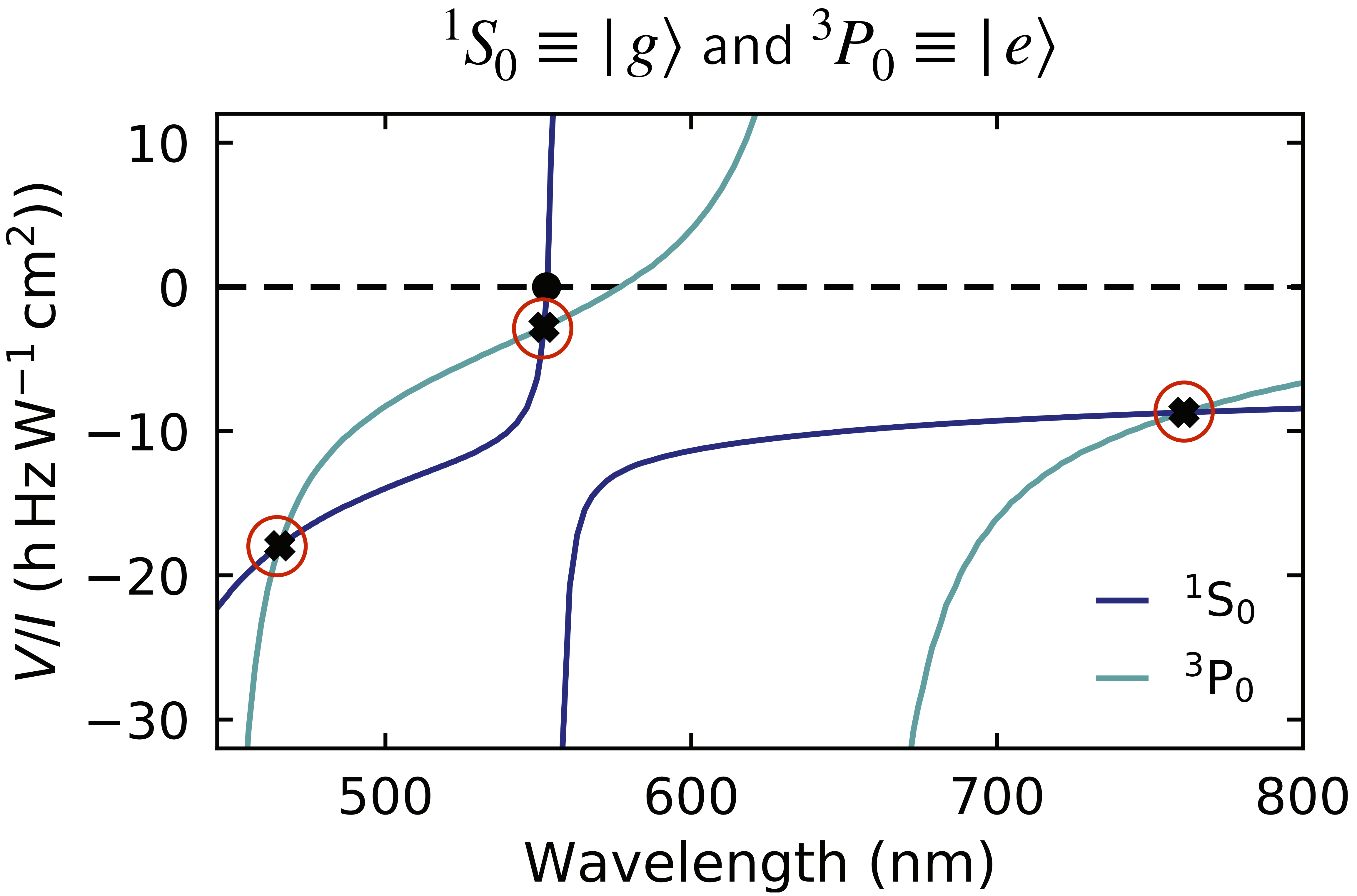


Use optical “clock” qubit states

State-dependent potentials

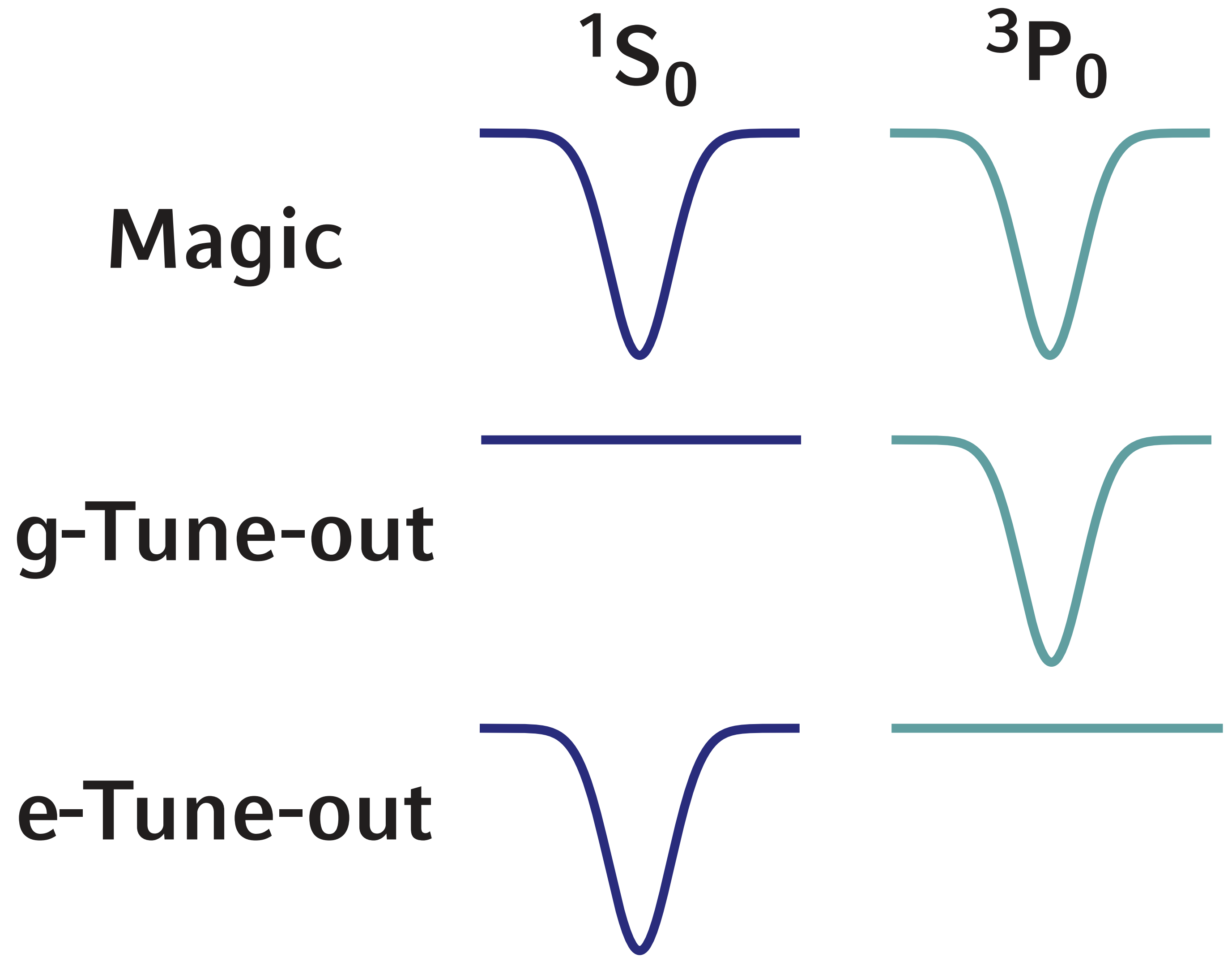
Magic

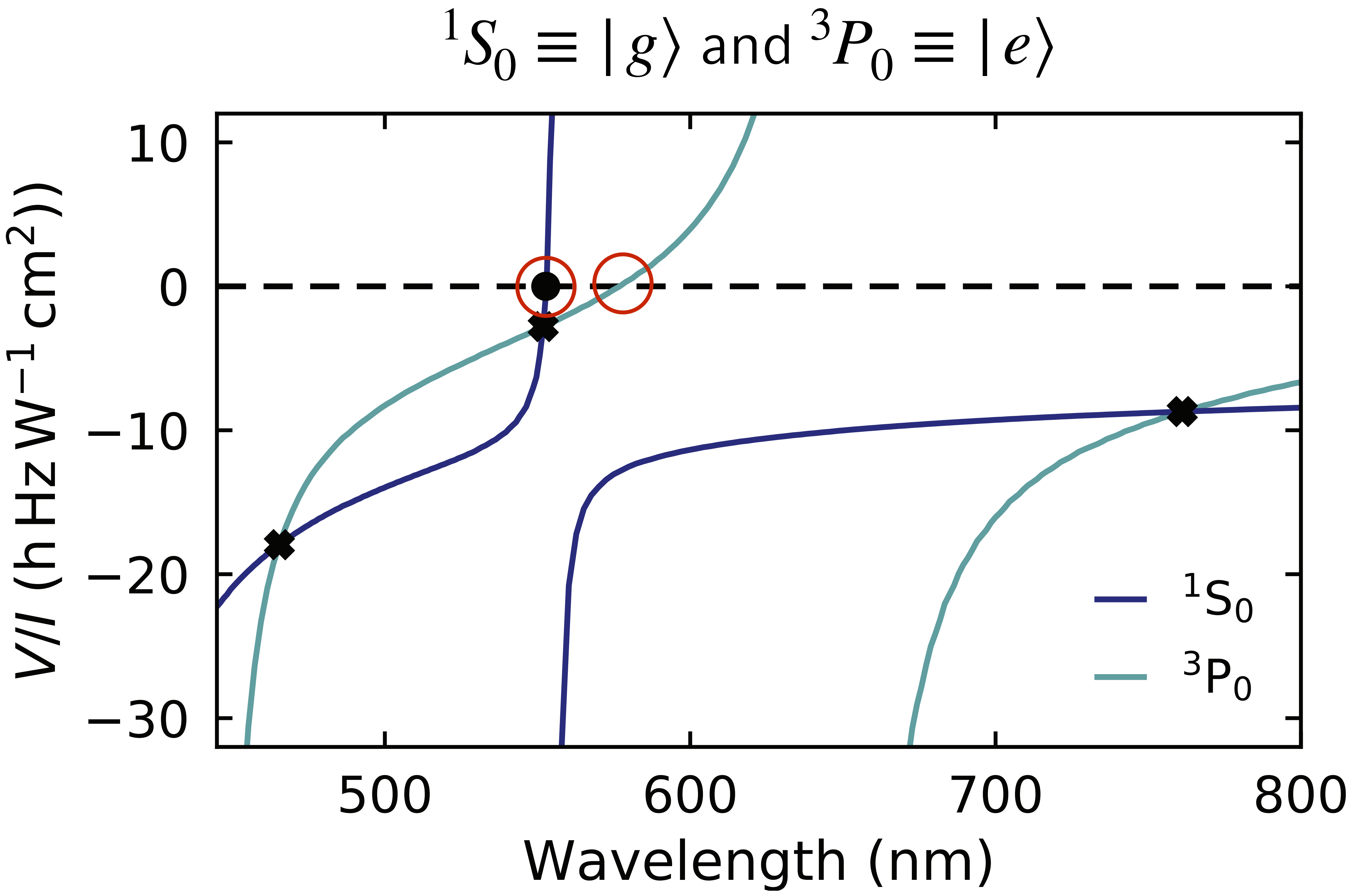




V. A. Dzuba and A. Derevianko, J. Phys. B: At. Mol. Opt. Phys. 43 074011 (2010)

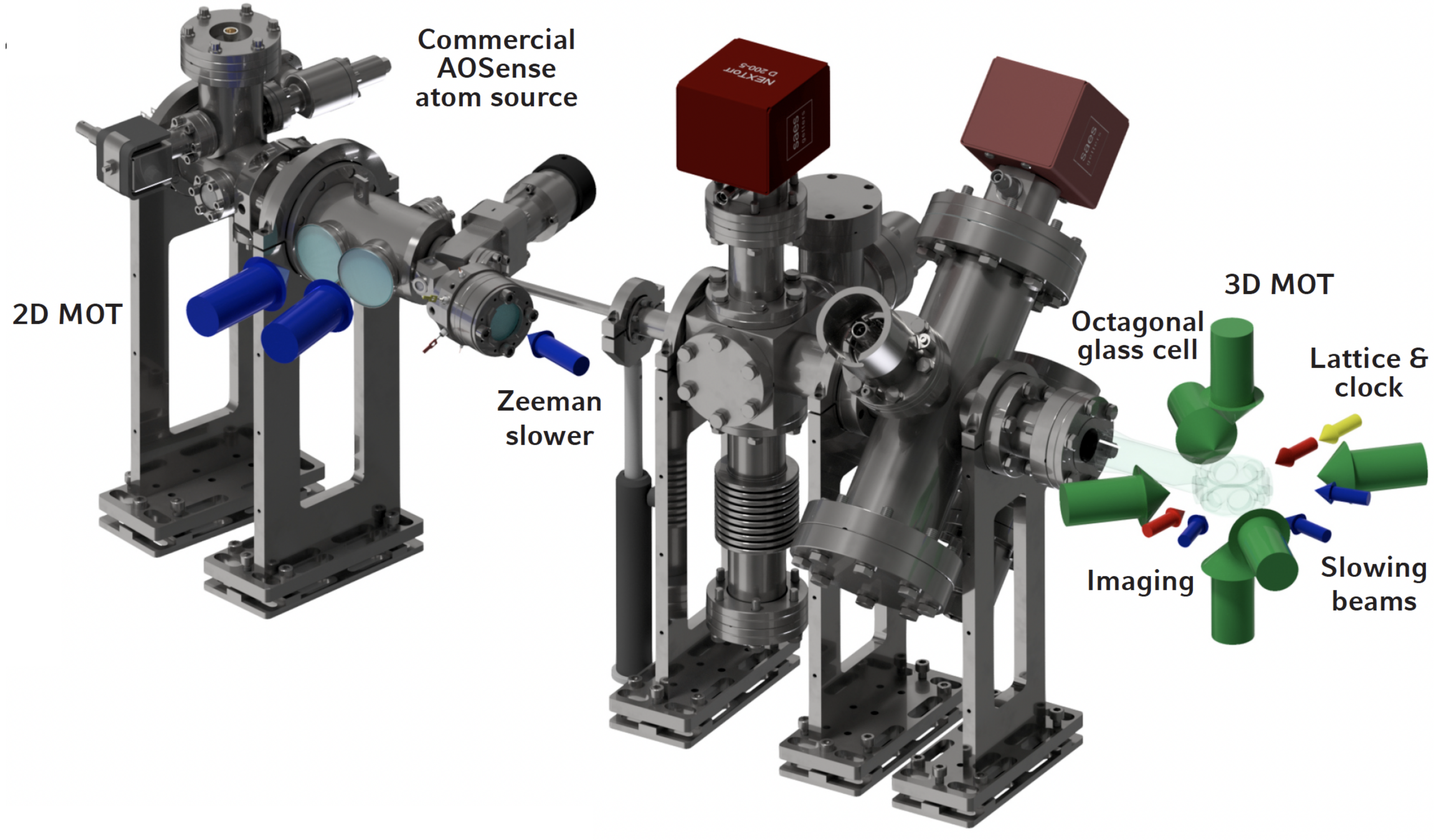
State-dependent potentials

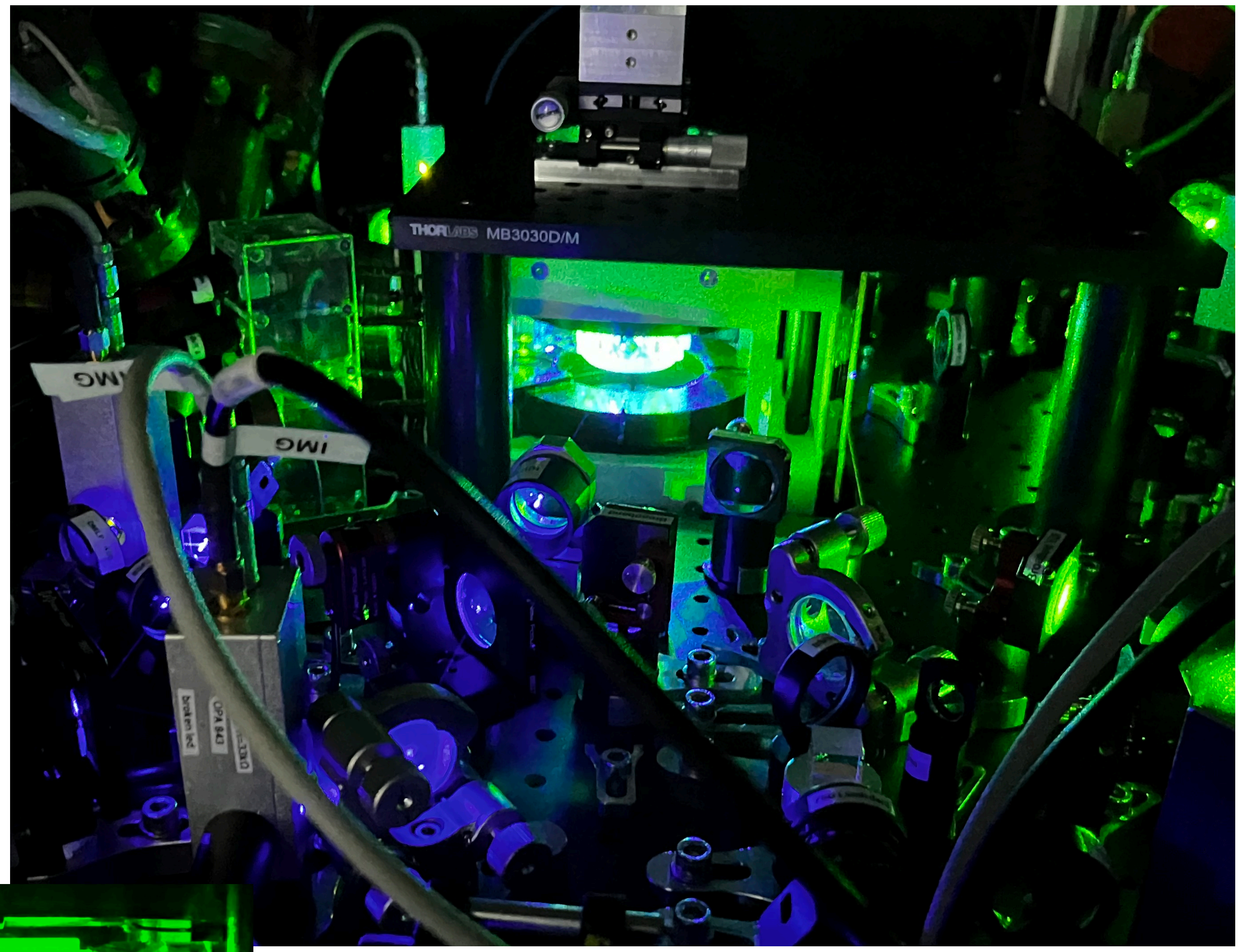


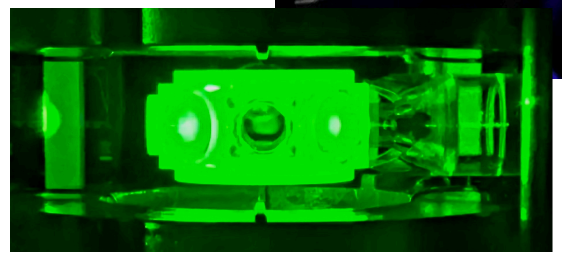


V. A. Dzuba and A. Derevianko, J. Phys. B: At. Mol. Opt. Phys. 43 074011 (2010)

Experimental setup





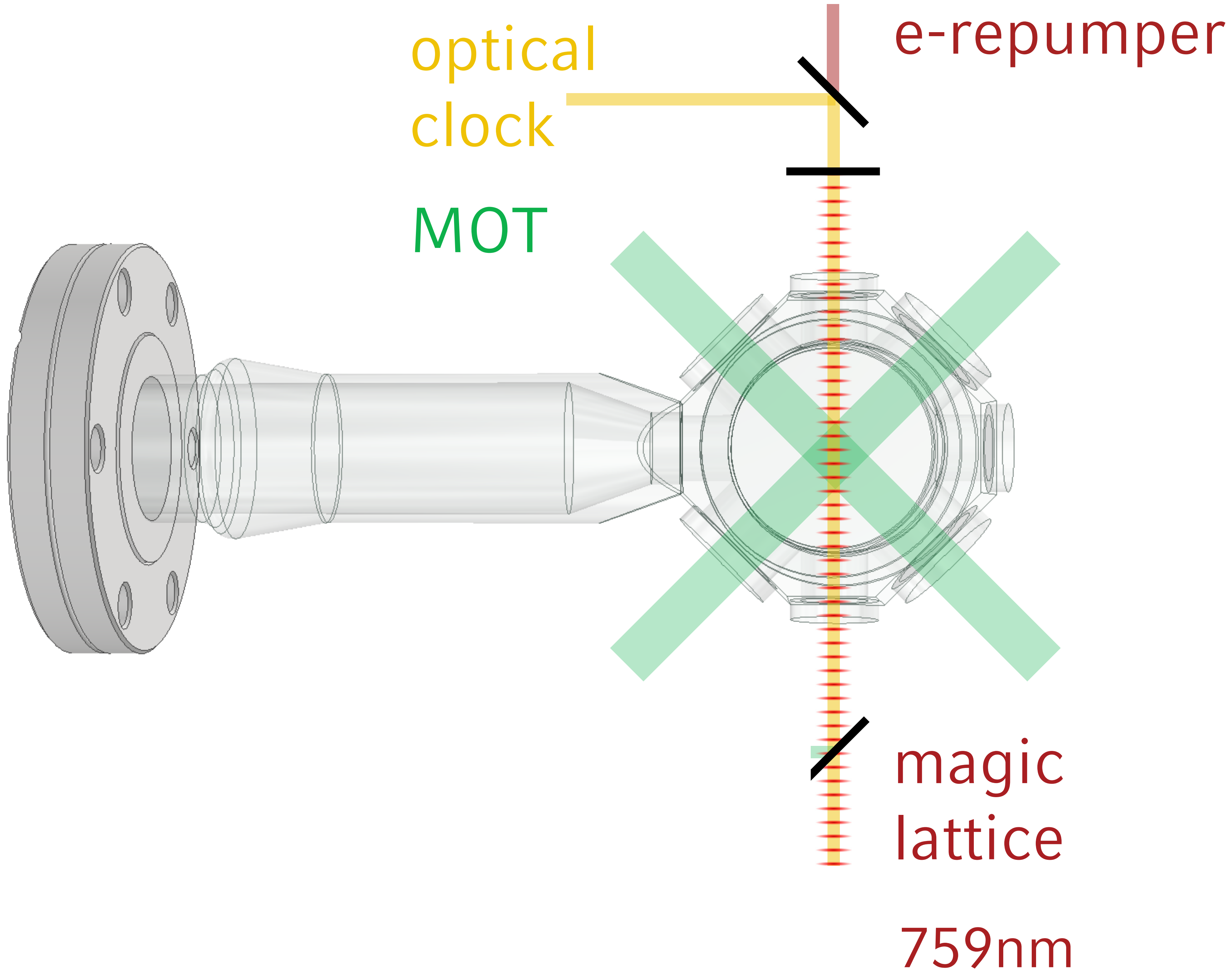


^{174}Yb MOT

Goal: Direct loading of lattice & rearrangement using optical tweezer

A. Young,..., A. Kaufman, arXiv:2202.01204

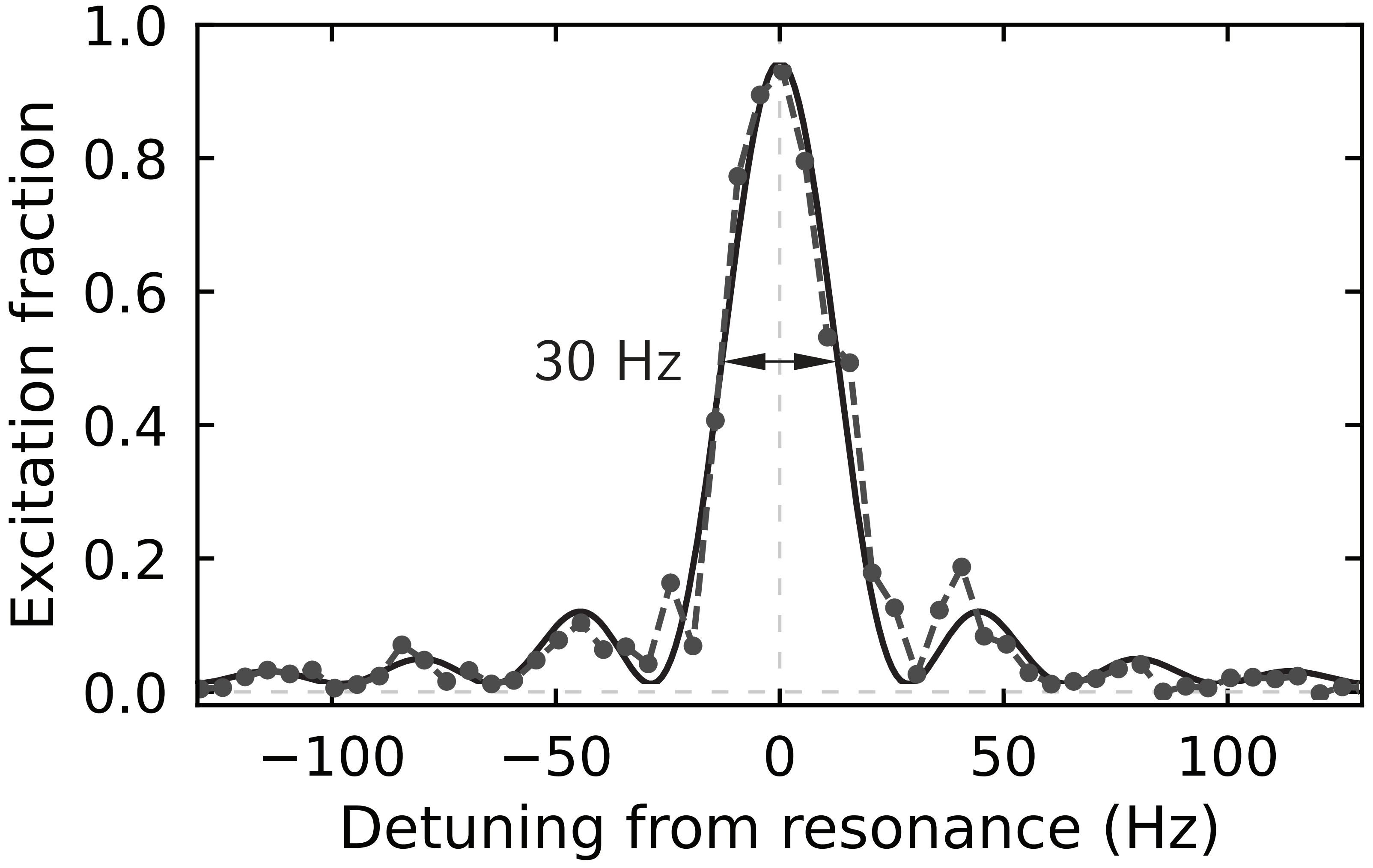
Optical clock spectroscopy



1D lattice:

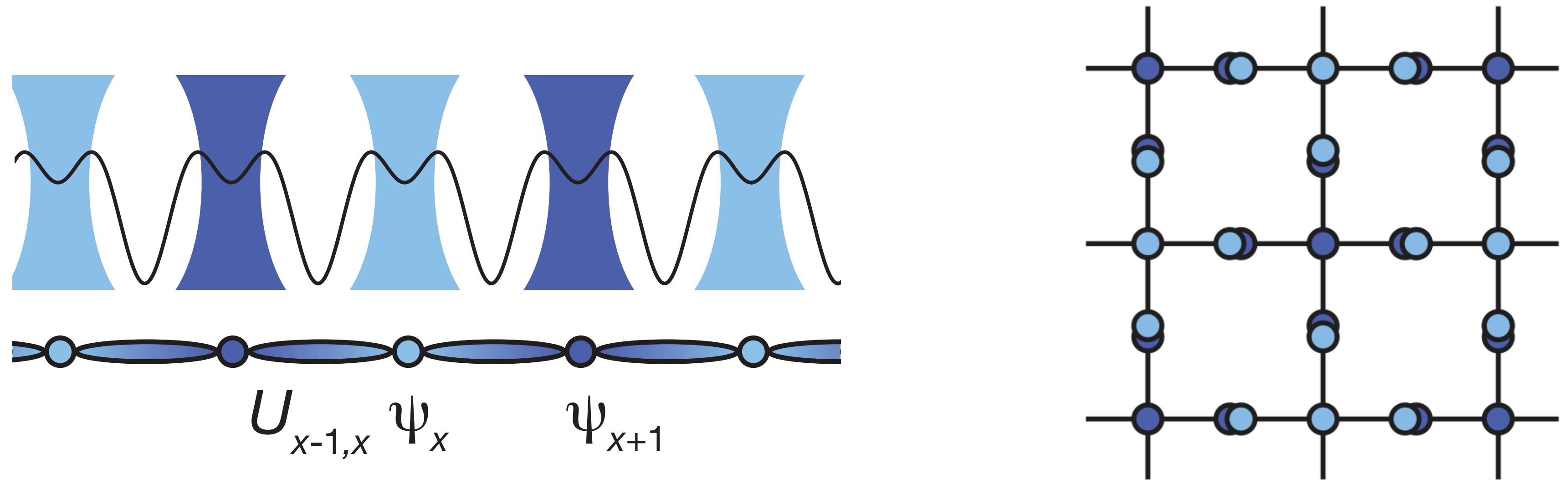
759nm, ~600Er,

~10^5 atoms @ 15μK



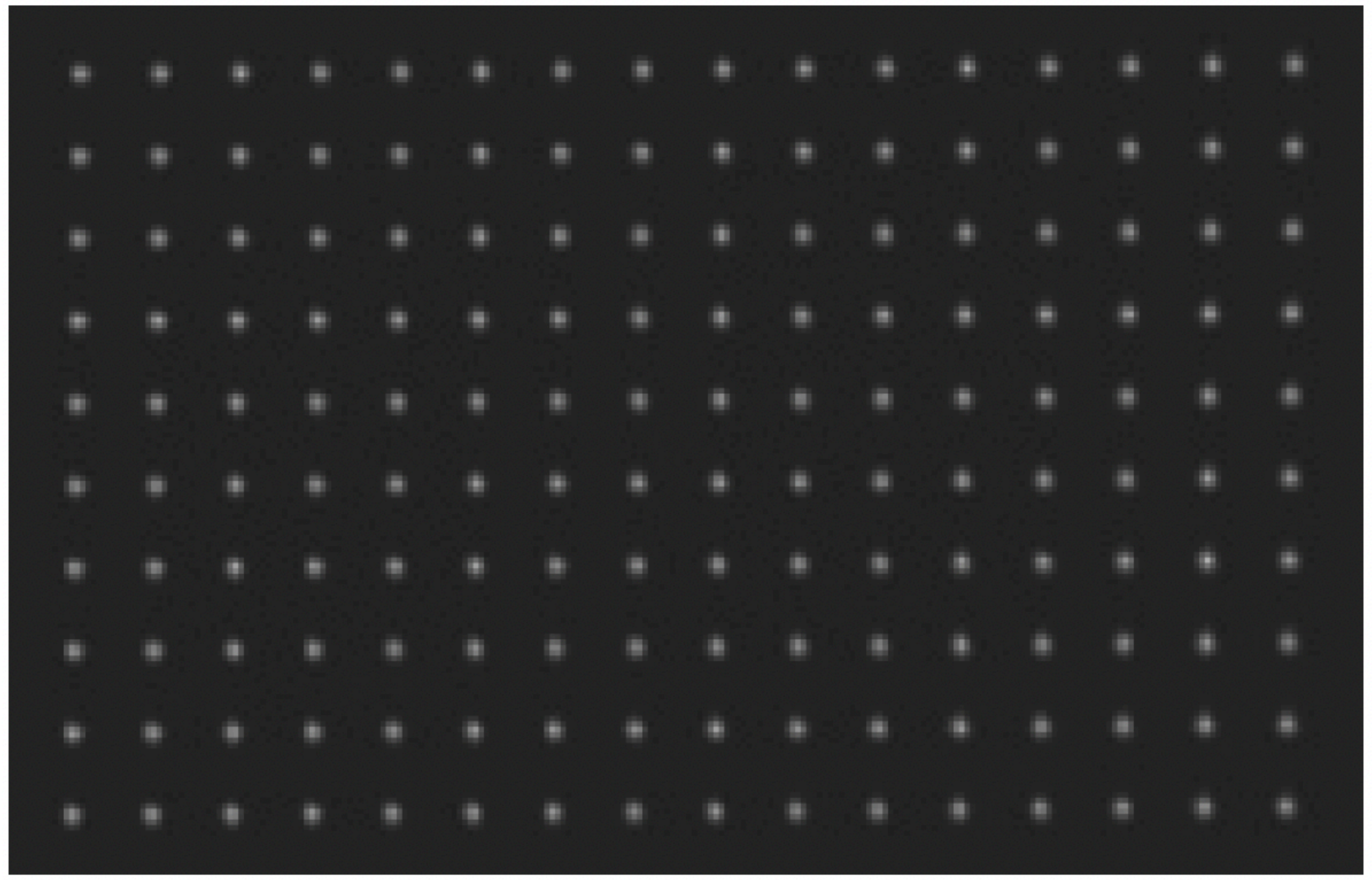
Summary & Outlook

New platform for simulating U(1) LGTs with fermionic Yb



- Extended lattices in 1&2D
- Possible extension to non-Abelian using **SU(N) sym. interactions** ^{171}Yb (I=1/2), ^{173}Yb (I=5/2)

Loading atoms into tweezer

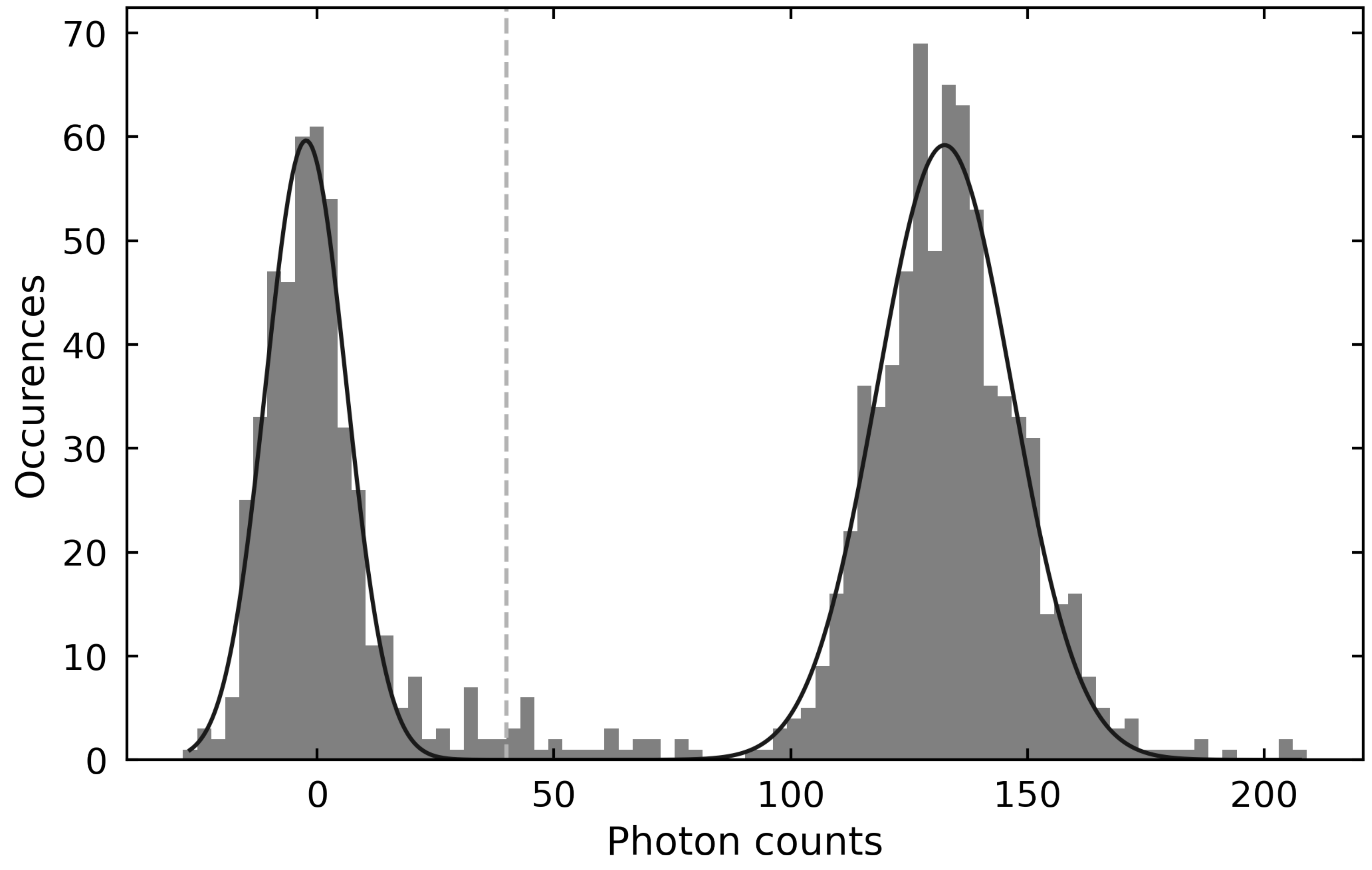


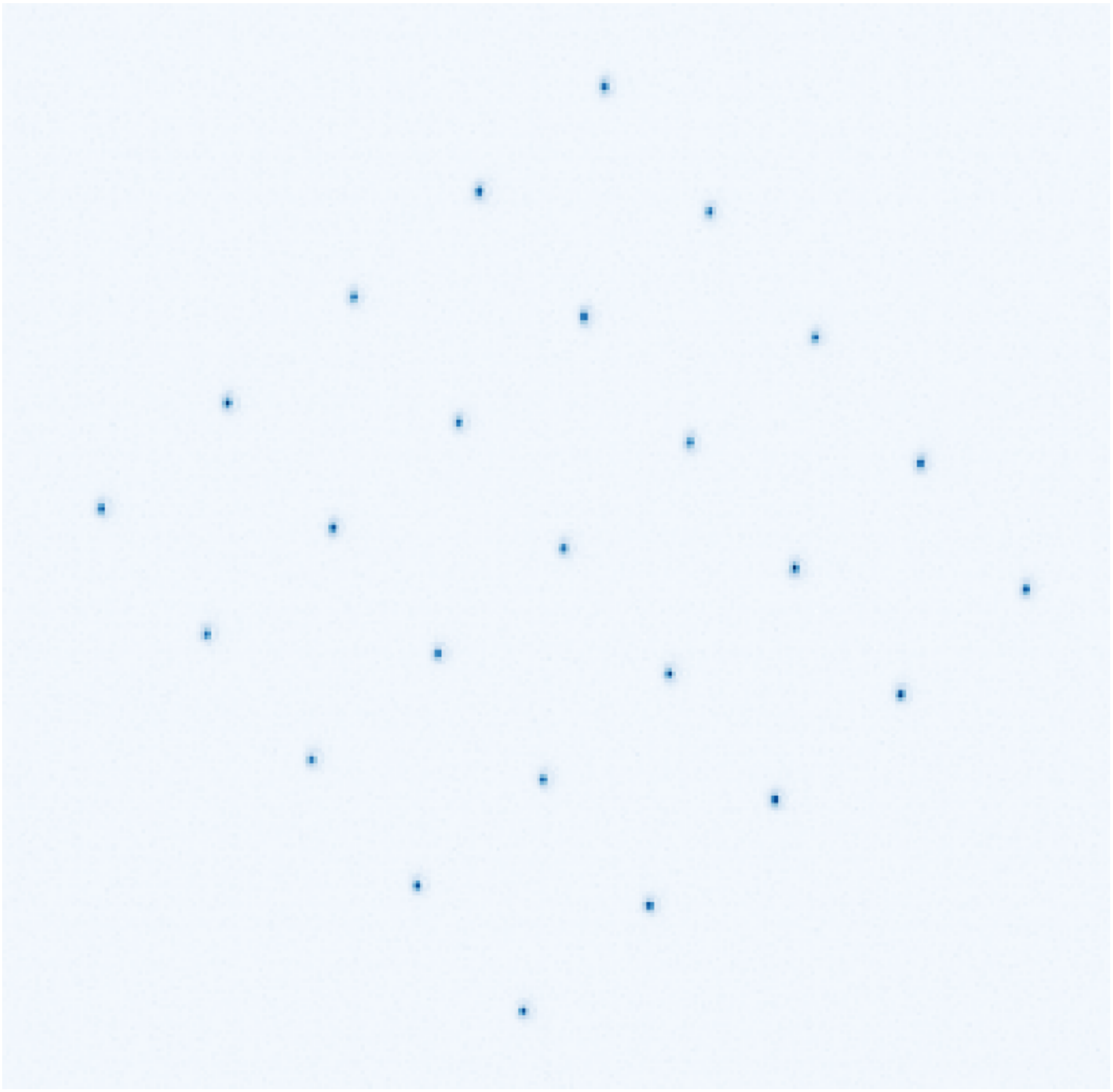
Optical Test Setup, Strehl ratio >0.85

Recent Update

^{174}Yb atoms in tweezer array

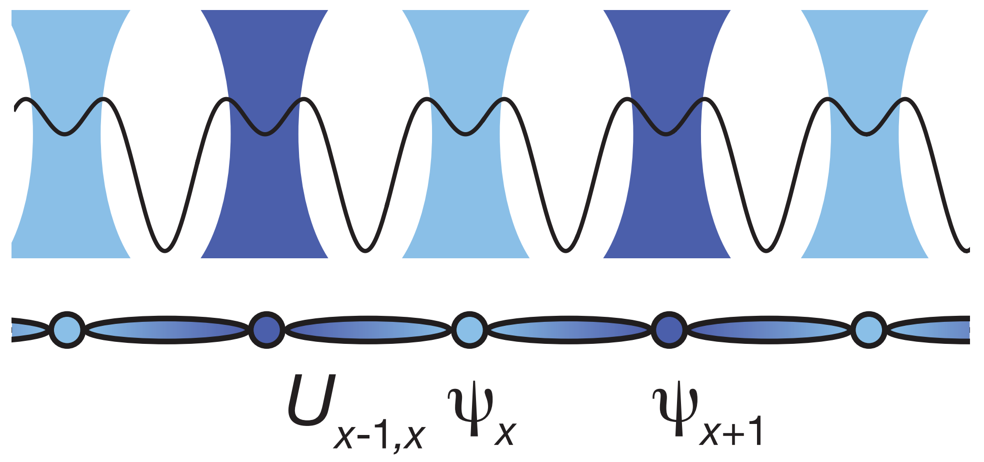
- Short cycle times < 0.5s
- Good imaging fidelity

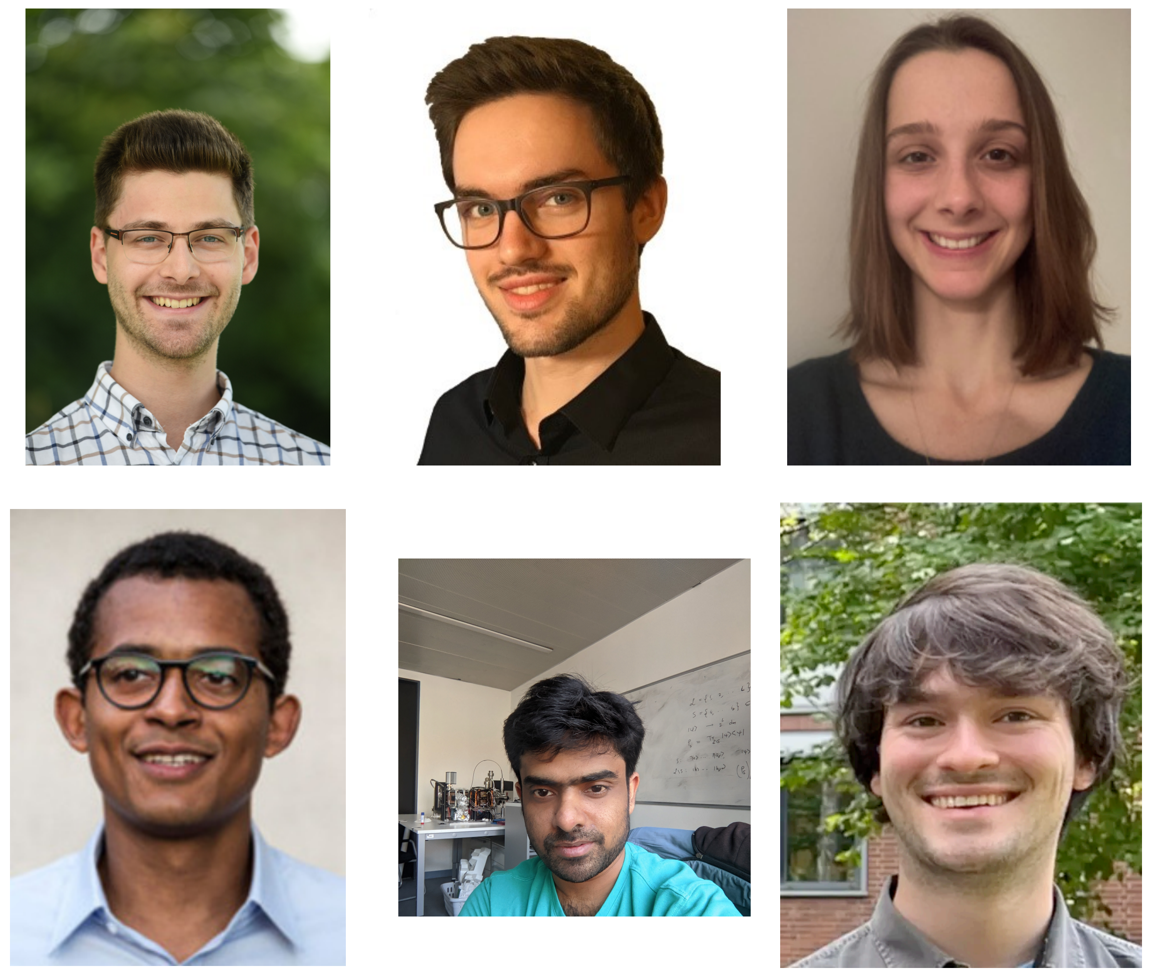




Yb hybrid lattice-tweezer lab

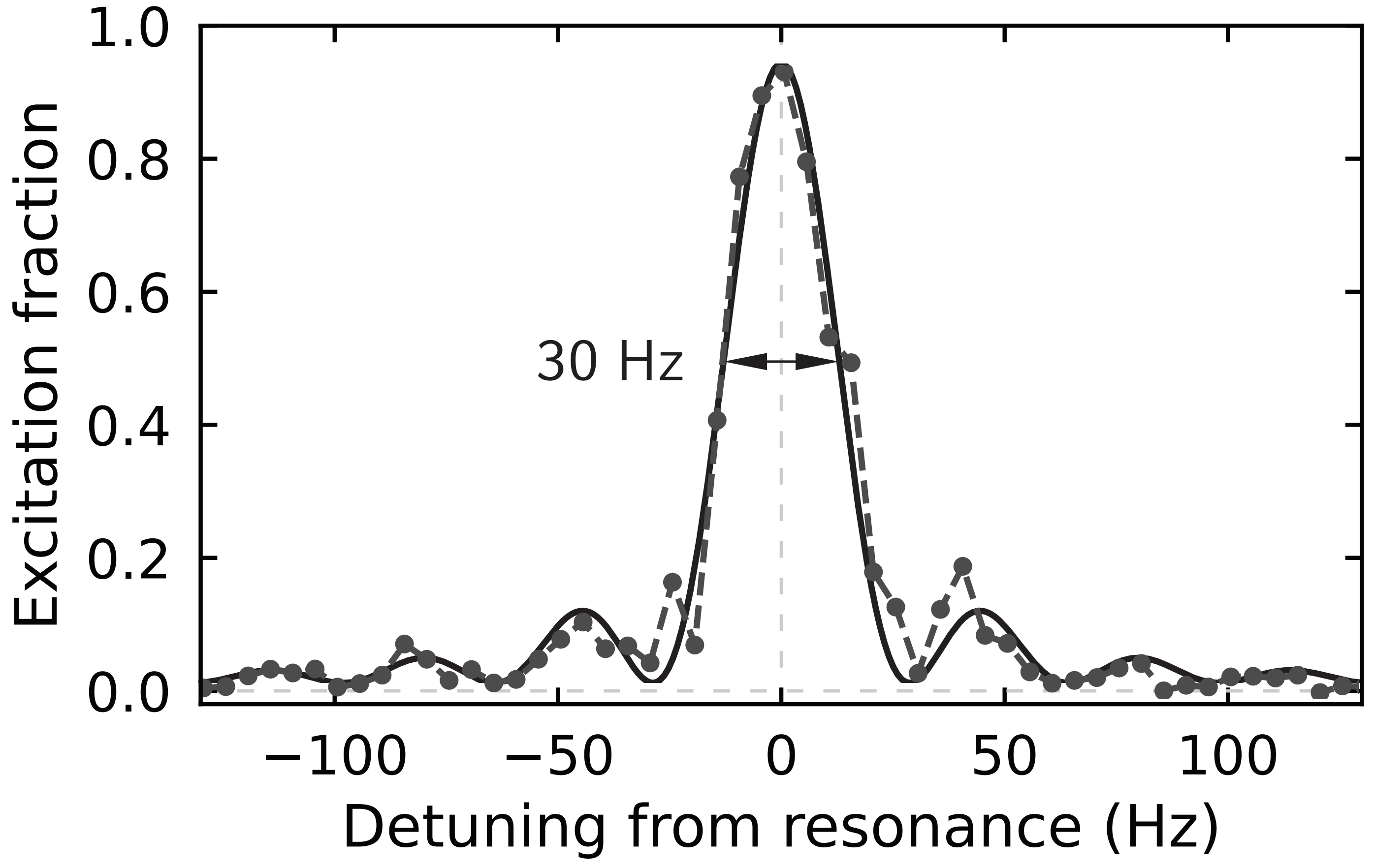
U(1) lattice gauge theories with fermionic Yb in 1D and 2D





Etienne Staub,
Tim Höhn,
Clara Bachorz
Nelson Darkwah Oppong
Bharath Hebbe
Madhusudhana
Dalila Robledo,
Guillaume Brochier
David Gröters

Clock spectroscopy



F. M. Surace, P. Promholz, N. Darkwah Oppong, M. Dalmonte, MA, arXiv:2301.03474

Cs quantum gas microscope

Ignacio Perez

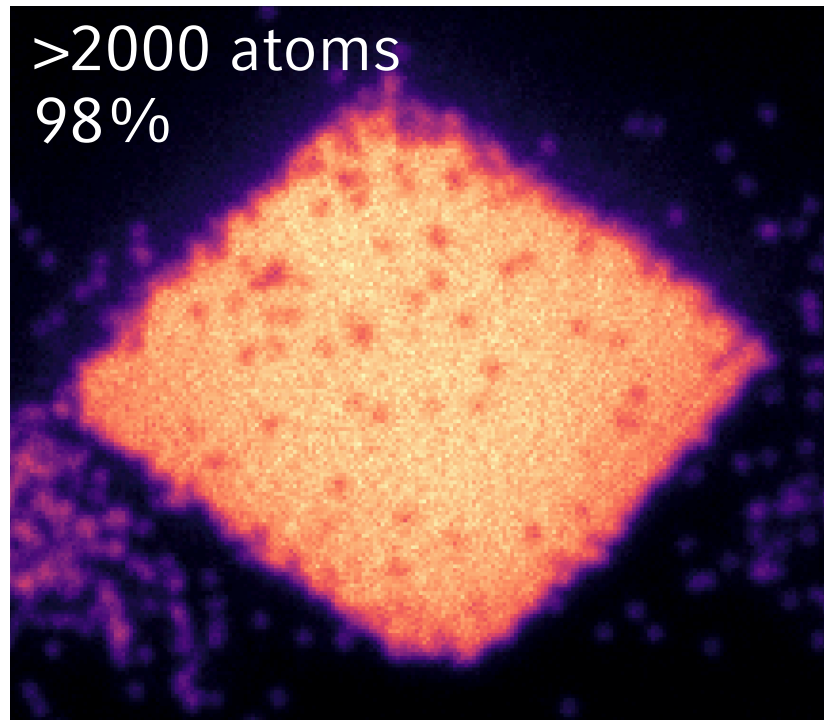
Simon Karch

Christian Schweizer

Scott Hubele

Sophie Häfele

Alexander Impertro,
Cesar Cabrera
Hendrik von Raven,
Julian Wienand
Till Klostermann,
MA, Immanuel Bloch



Cs atoms

T. Klostermann, ..., MA, Phys. Rev. A **105**, 043319 (2022); Alexander Impertro, ..., MA, arXiv:2212.11974

Thank you