A novel fermionic hybrid tweezer-lattice platform for quantum simulation of U(1) LGTs in 2+1D

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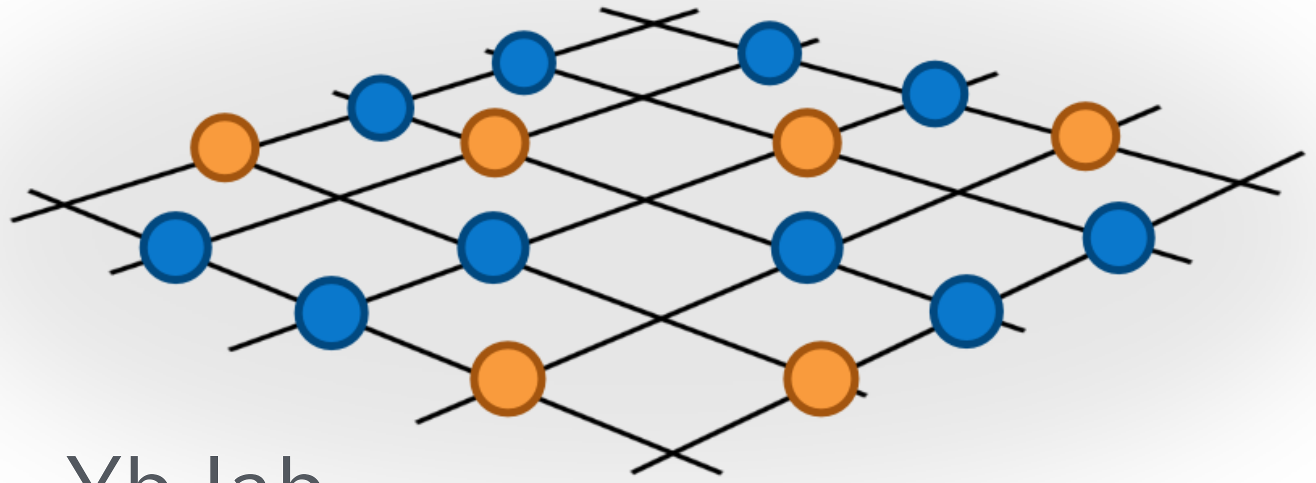
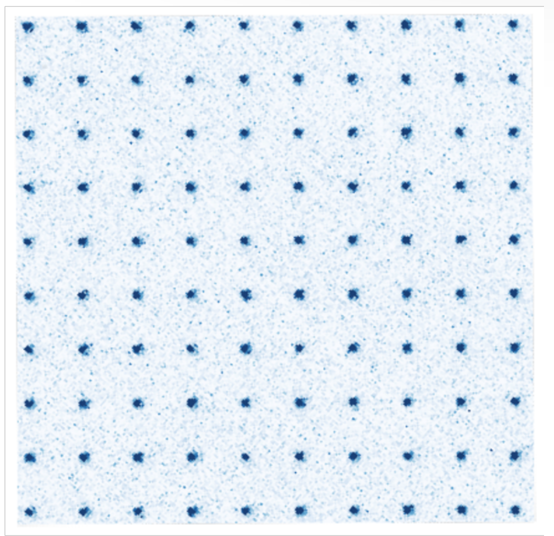
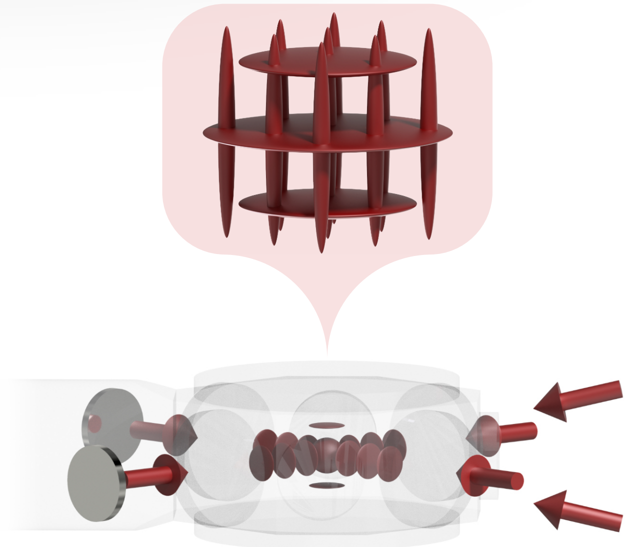
Ludwig-Maximilians Universität München
Munich Center for Quantum Science & Technology

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



Yb lab

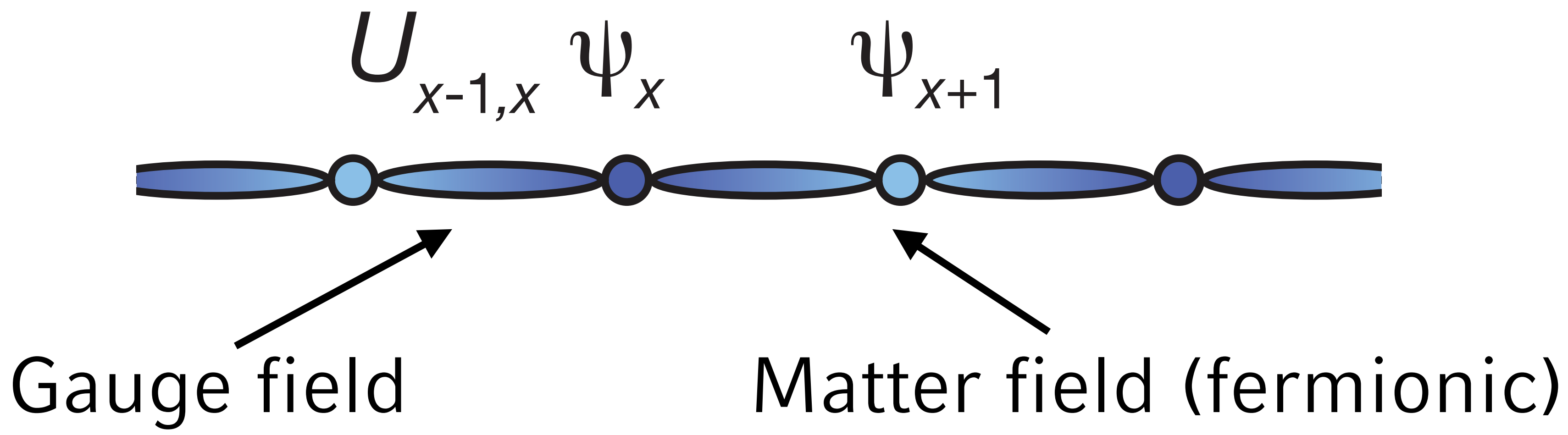




LMU LUDWIG-MAXIMILIANS-UNIVERSITÄT MÜNCHEN | MCQST | MUNICH QUANTUM CENTER | Munich Quantum Valley | MPQ | PASQuanS2 | GEFÖRDERT VOM Bundesministerium für Bildung und Forschung | DFG Deutsche Forschungsgemeinschaft | erc European Research Council | Funded by the European Union

Gauge theories

Lattice gauge theories:



K. G. Wilson

Challenges for Quantum simulation:

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

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)

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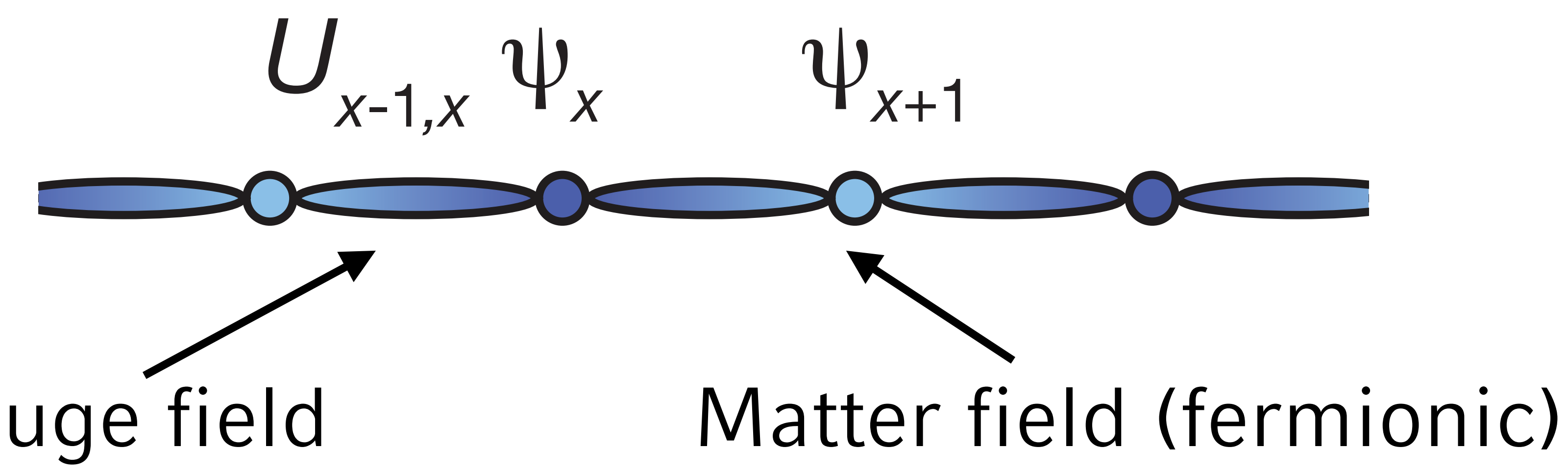

K. G. WILSON

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

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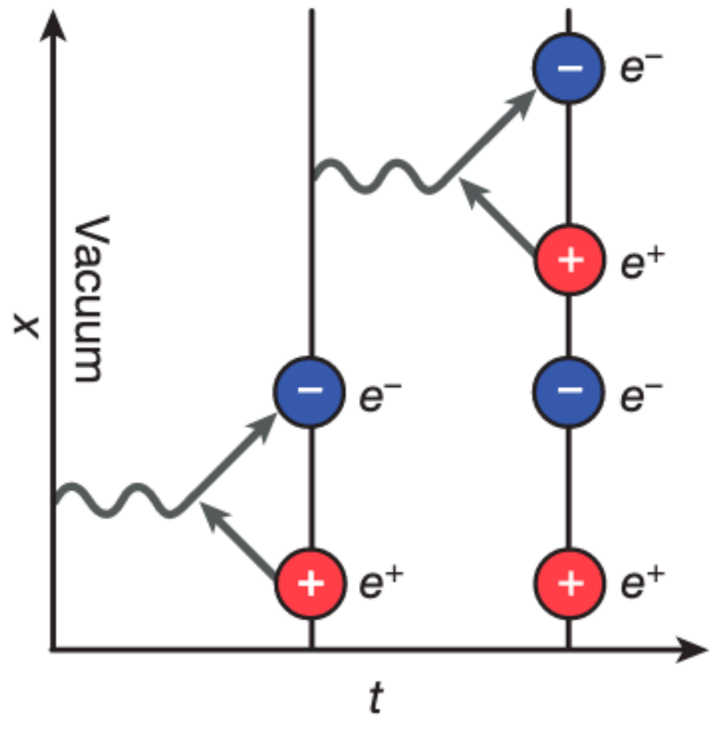
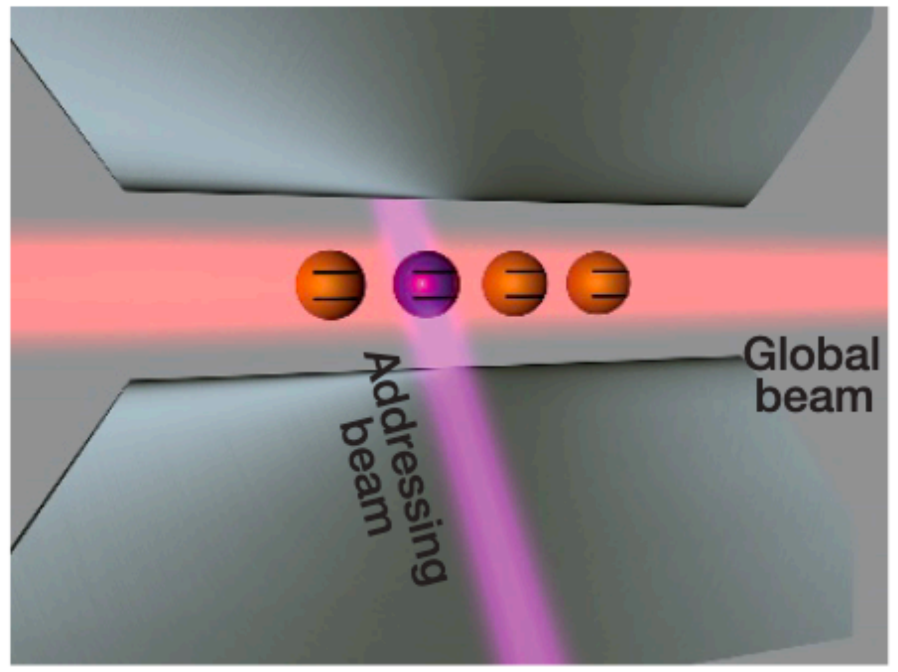
State-of-the-art

Few-ion quantum simulation





E. A. Martinez *et al.* Nature **534**, 516-519 (2016)
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Gauge-fields are eliminated ↔ exotic long-range interactions

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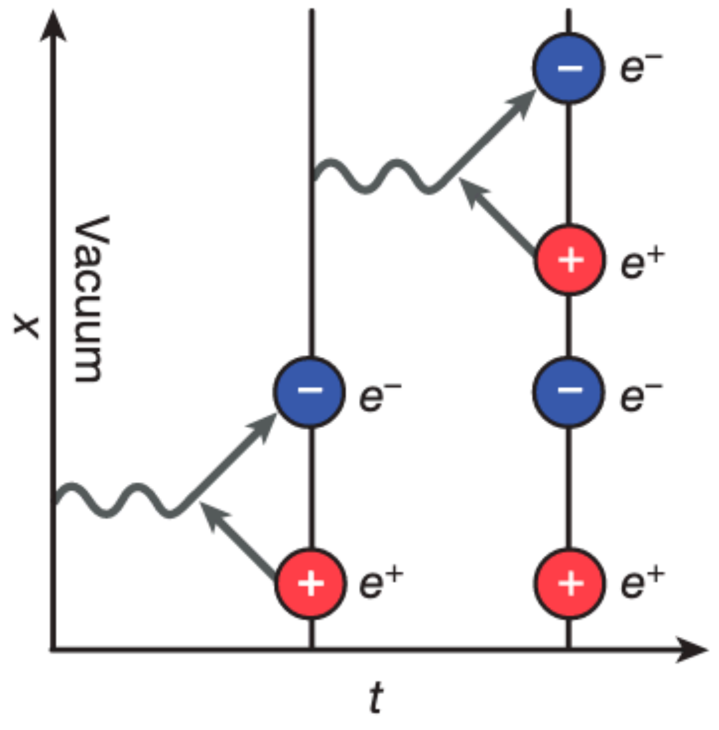

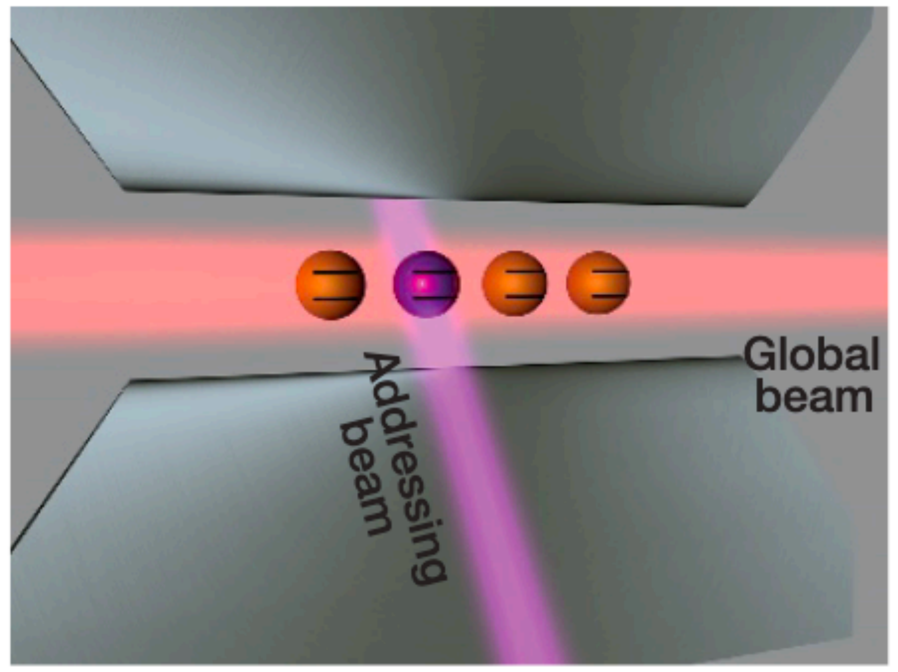

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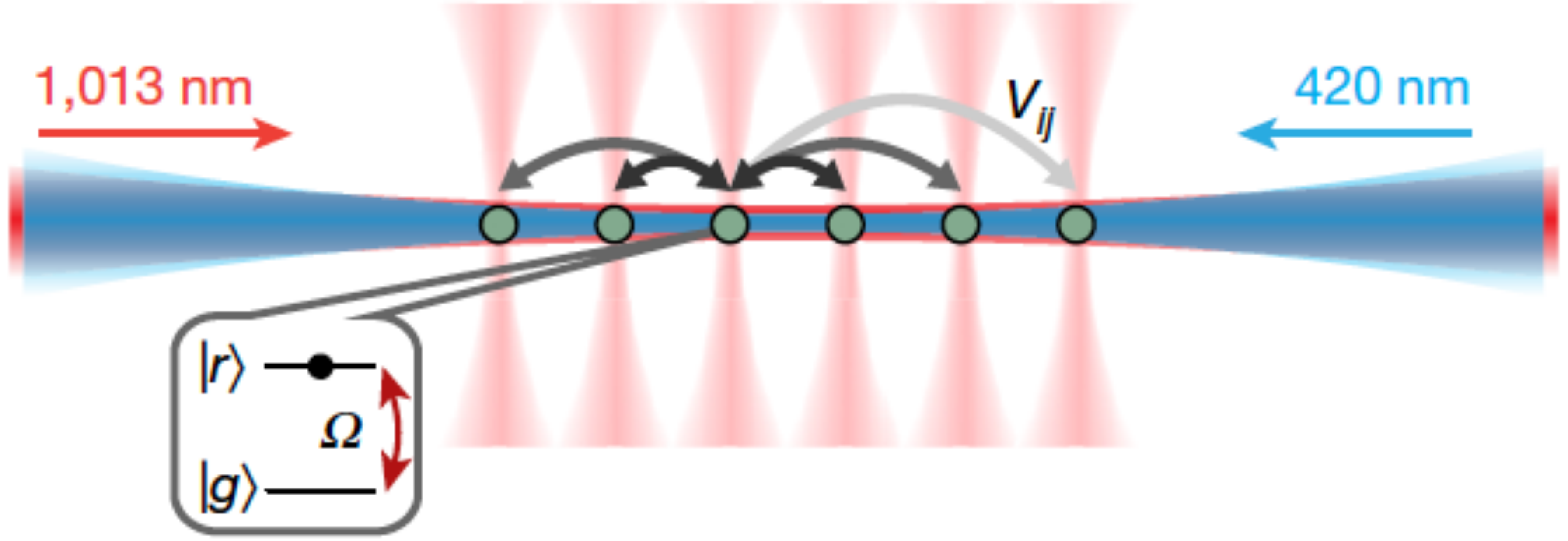
Gauge-fields are eliminated ↔ exotic long-range interactions

Rydberg atom arrays

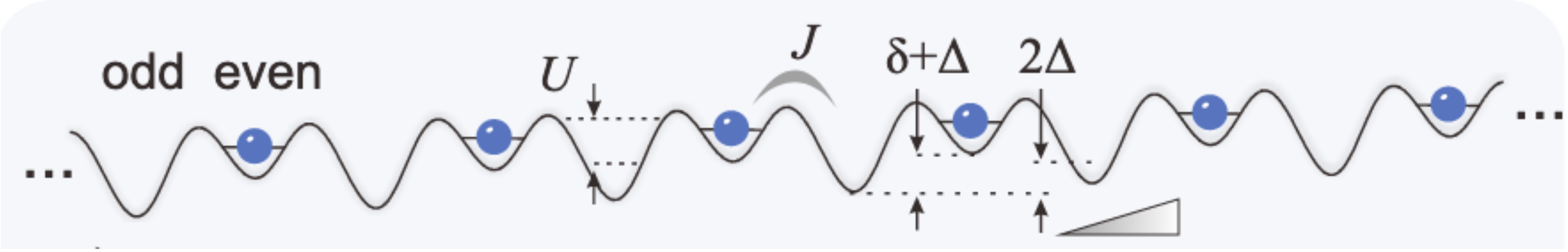


H. Bernien *et al.* Nature **551**, 579 (2017);
F. M. Surace *et al.* Phys. Rev. X **10**, 021041 (2020)

Matter-fields are eliminated

State-of-the-art: cold atoms

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.*, PRL **131**, 050401 (2023); W.-Y. Zhang *et al.*, arXiv:2306.11794 ***(matter-fields eliminated)***

Building blocks: Z_2: Schweizer,..., Aidelsburger, Nat. Phys. **15**, 1168-1173 (2019)
U(1): A. Mil *et al.* Science **367**, 1128-1130 (2020)

Review: Halimeh, Aidelsburger, Grusdt, Hauke, Yang, arXiv:2310.12201

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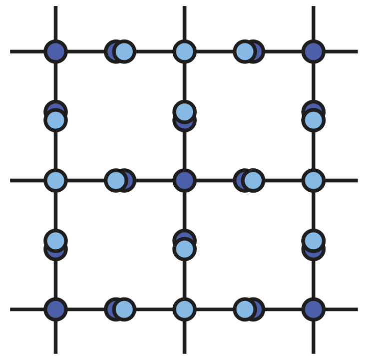
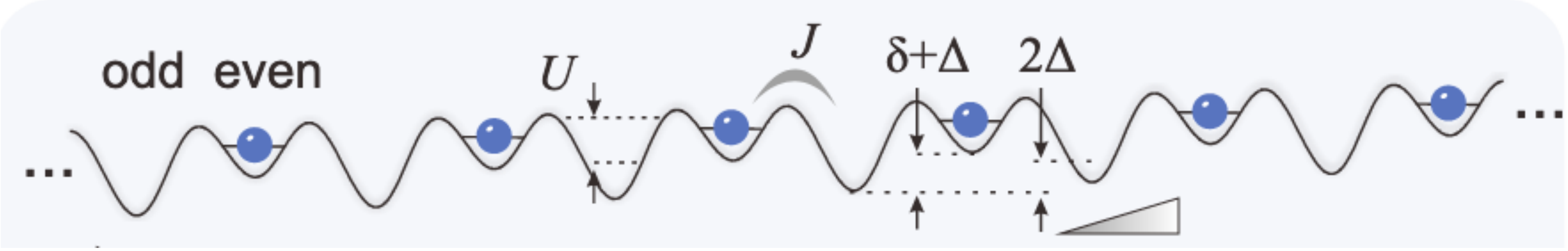


Bosonic atoms in tilted optical superlattices



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Our goal:

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

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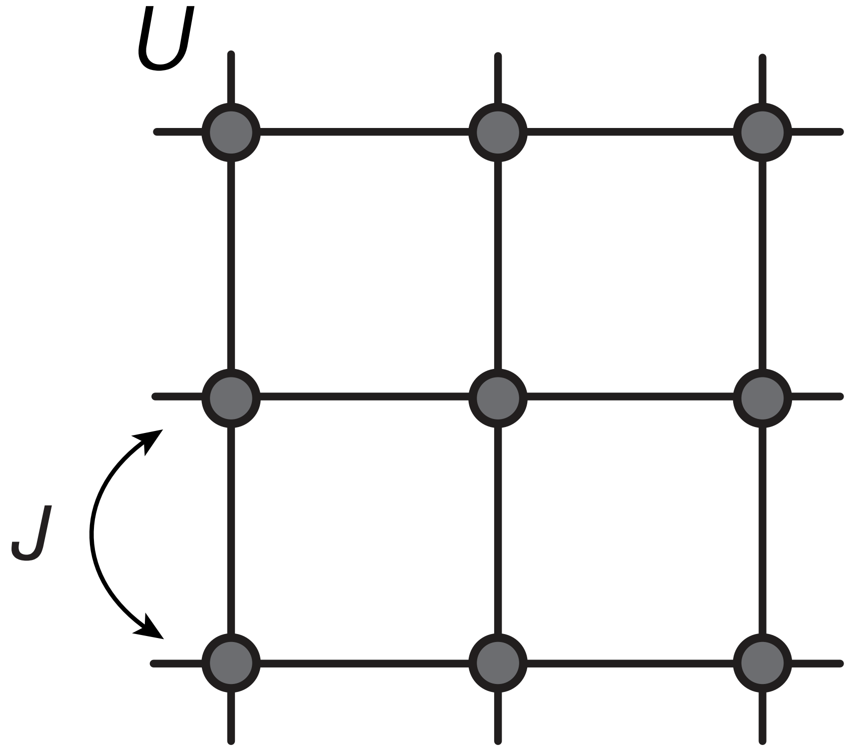
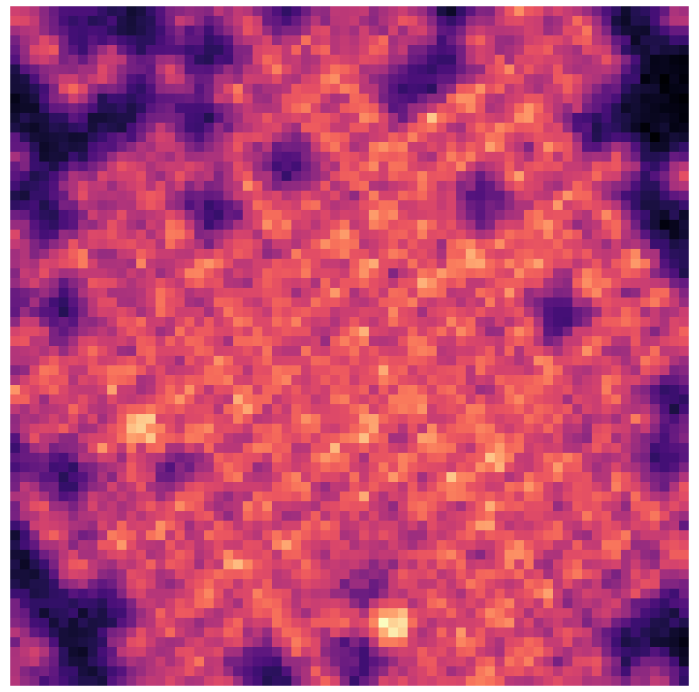
Novel fermionic tweezer-lattice experiment
- fast cycle times & local control

Quantum Gas Microscopy

Traditional approach for preparing low-entropy initial states





Cs atoms

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

C. Gross and I. Bloch, Science 357 (2017); C. Gross and W. Bakr, Nature Phys. **17**, 1316 (2021)

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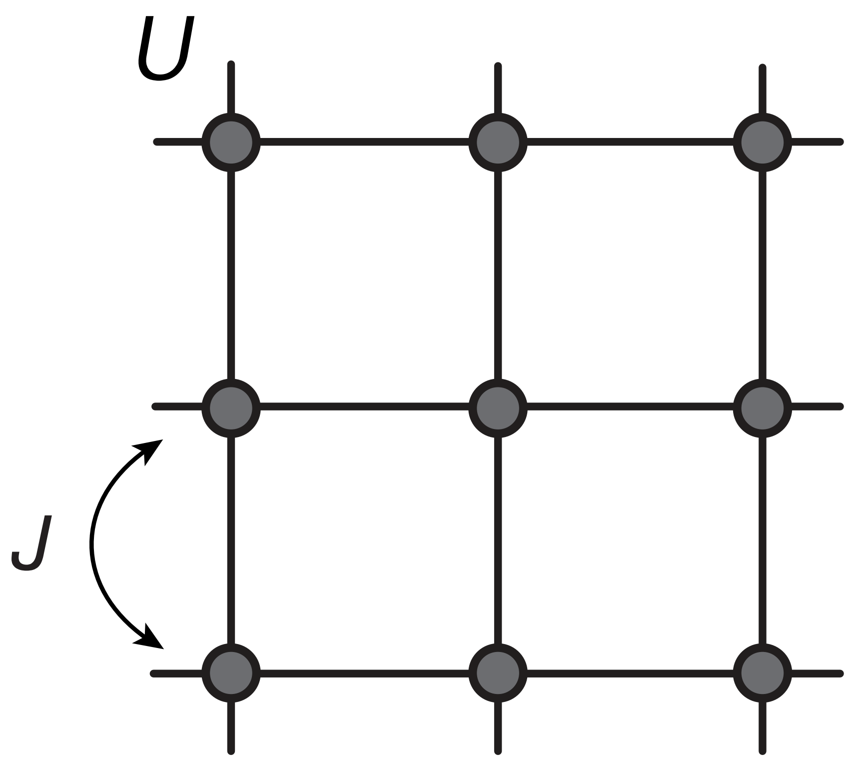
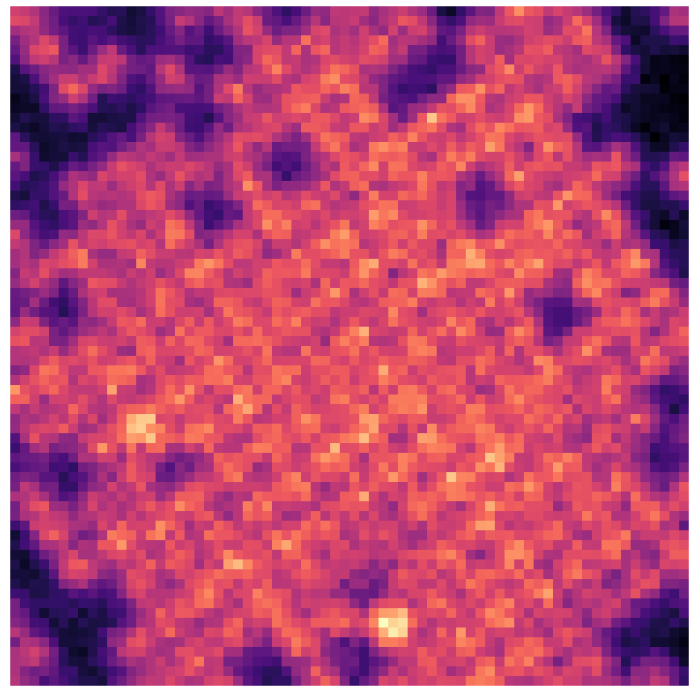
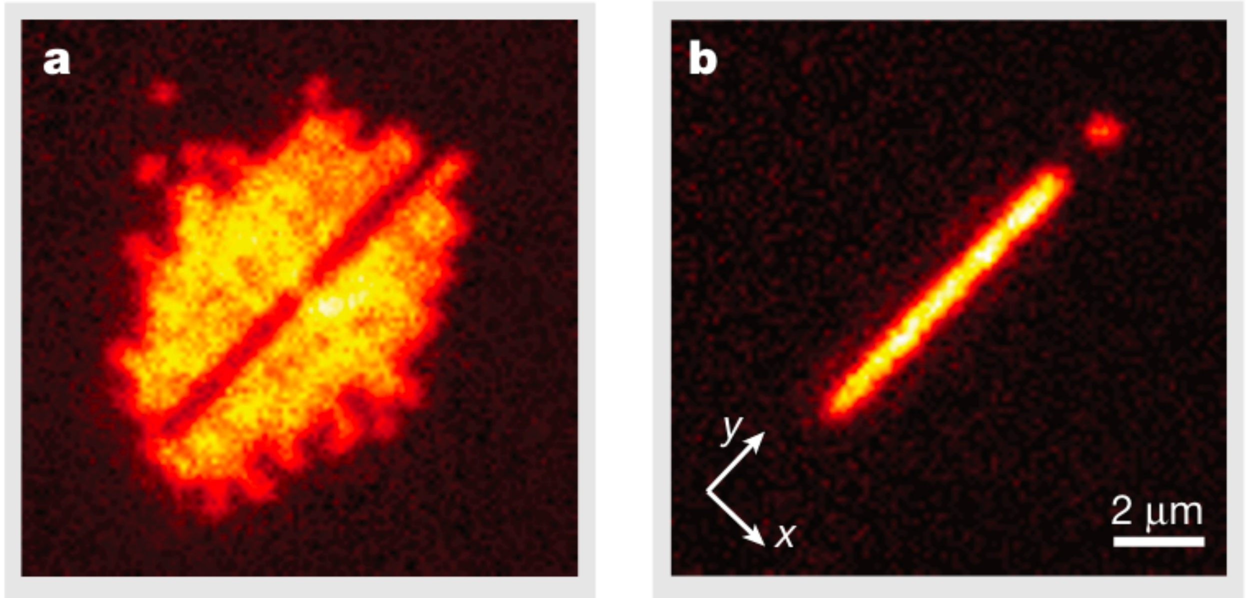




Cs atoms

"Cookie cut" arbitrary initial states



C. Weitenberg et al., Nature (2011)

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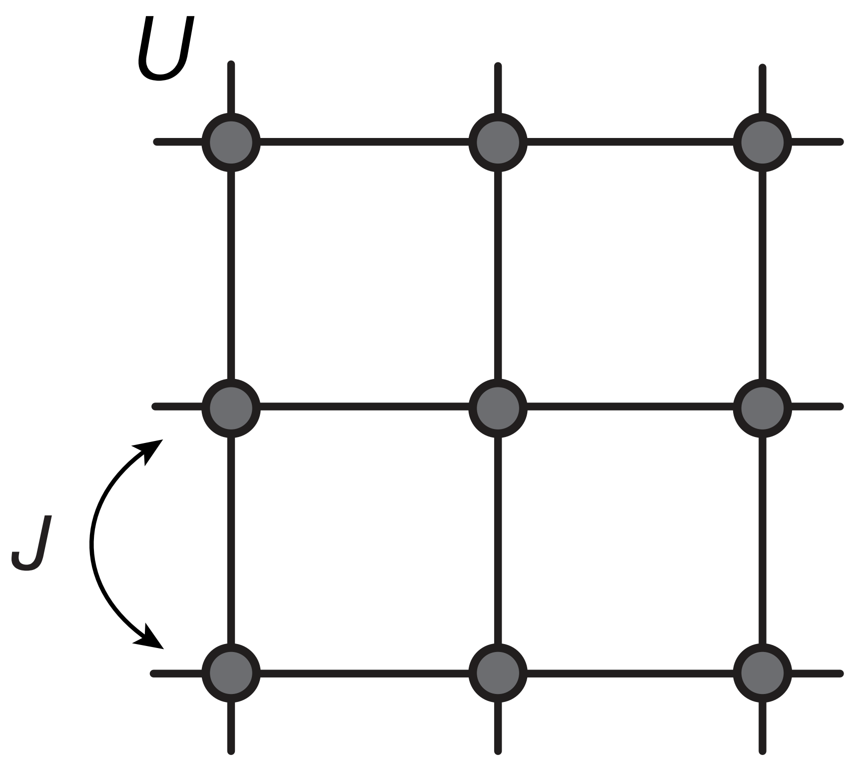

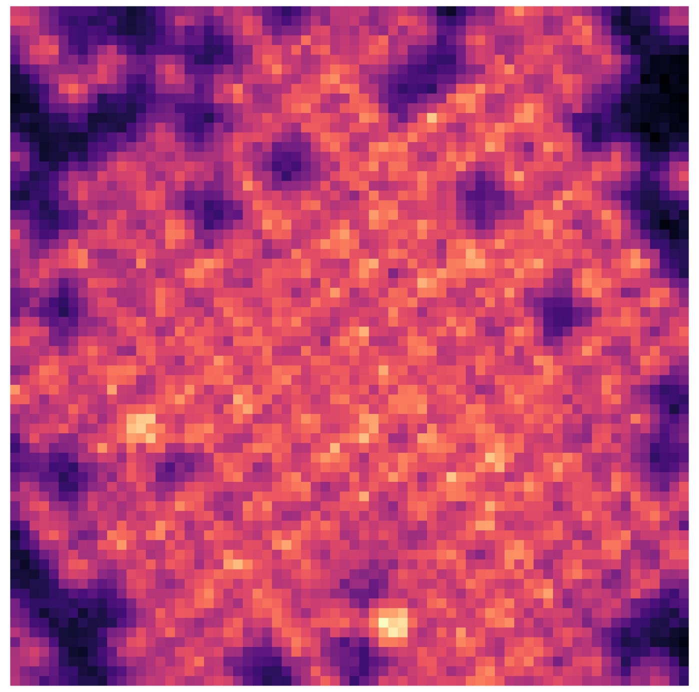

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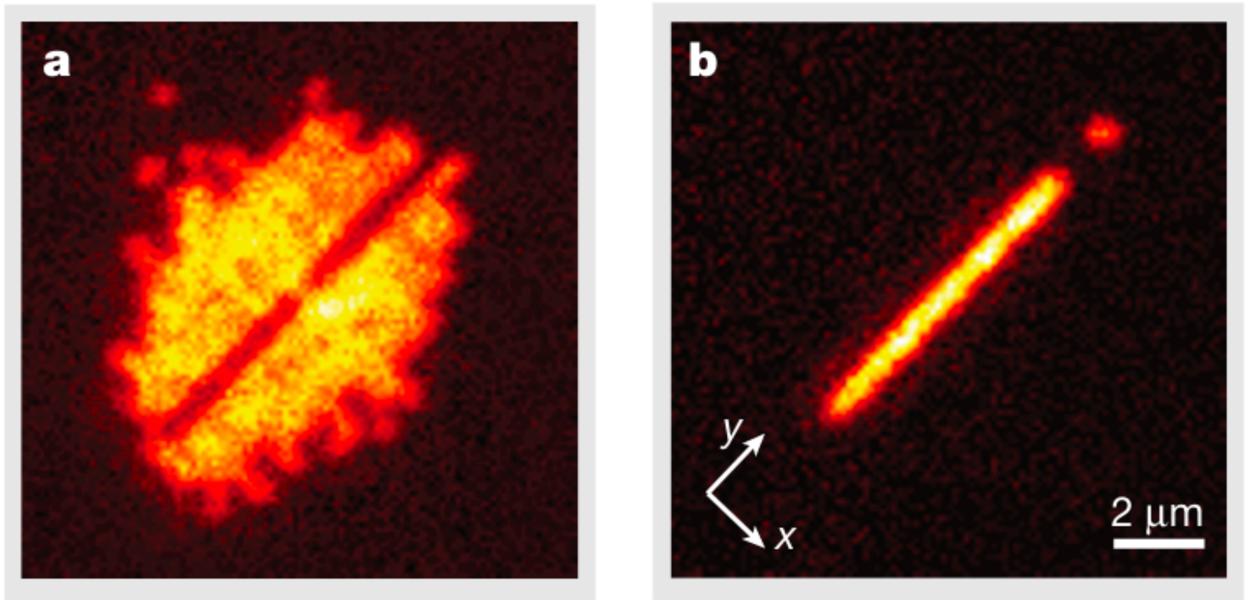

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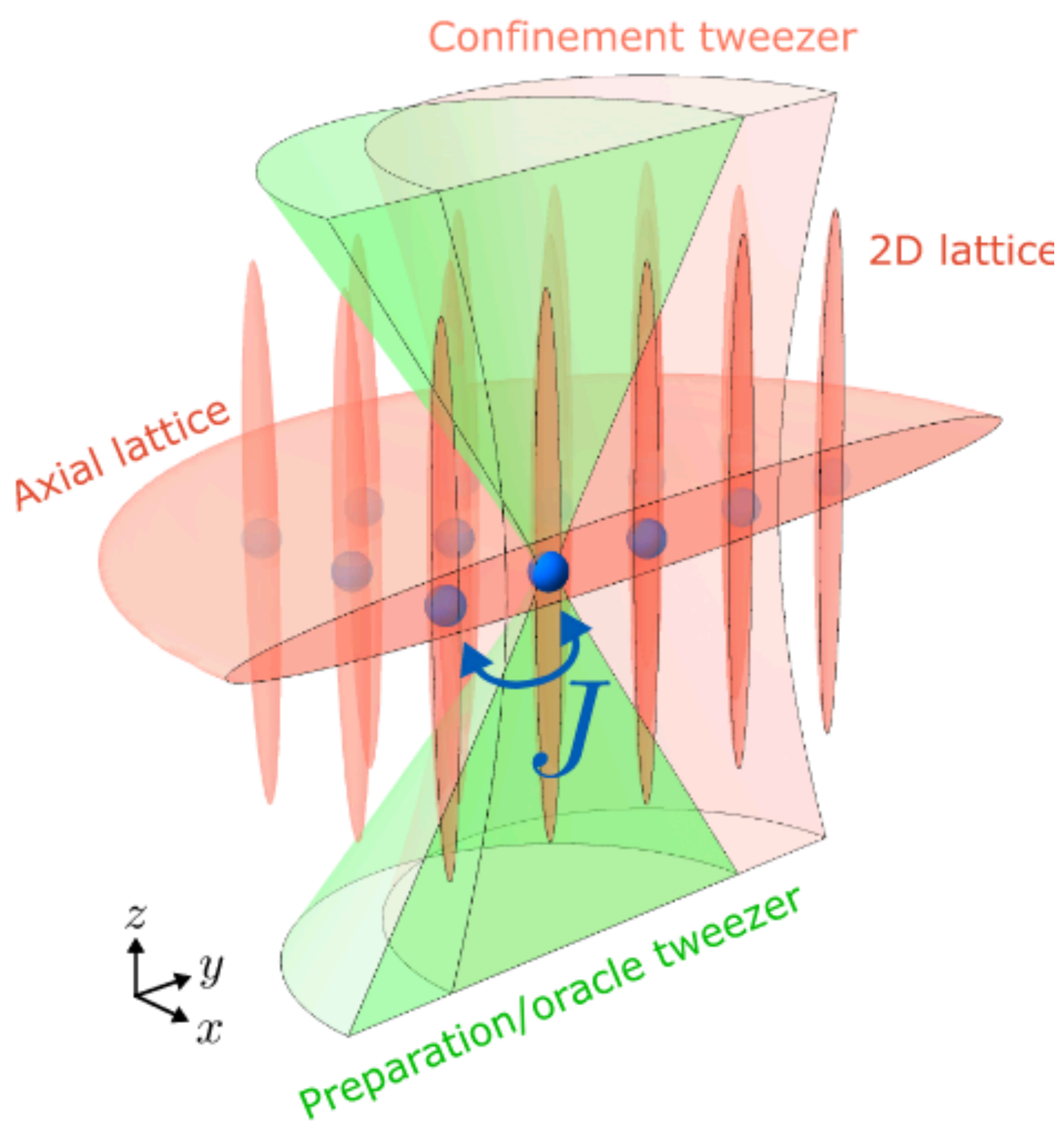
- Long cycle times ~20s
- Limited local control of tunnelings

C. Gross and I. Bloch, Science 357 (2017); C. Gross and W. Bakr, Nature Phys. **17**, 1316 (2021)

Tweezer-assisted state preparation



Programmable Bose-Hubbard system:
Young,..., Kaufman, Science **377**, 885 (2022)

Protocol for state preparation:

see also early work by C. Regal and more recently by W. Bakr, I. Bloch, J. Zeiher and Atom Computing

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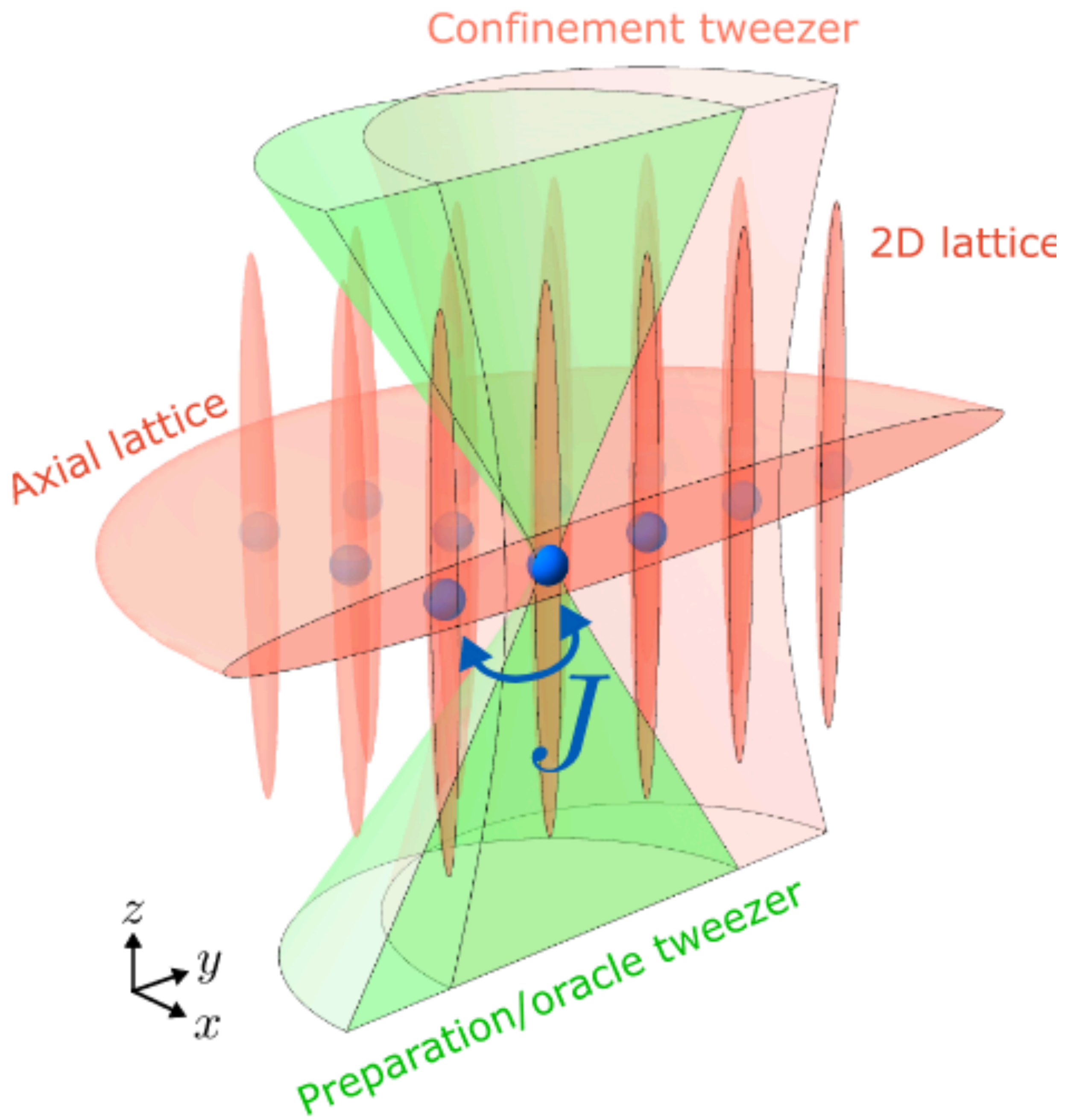

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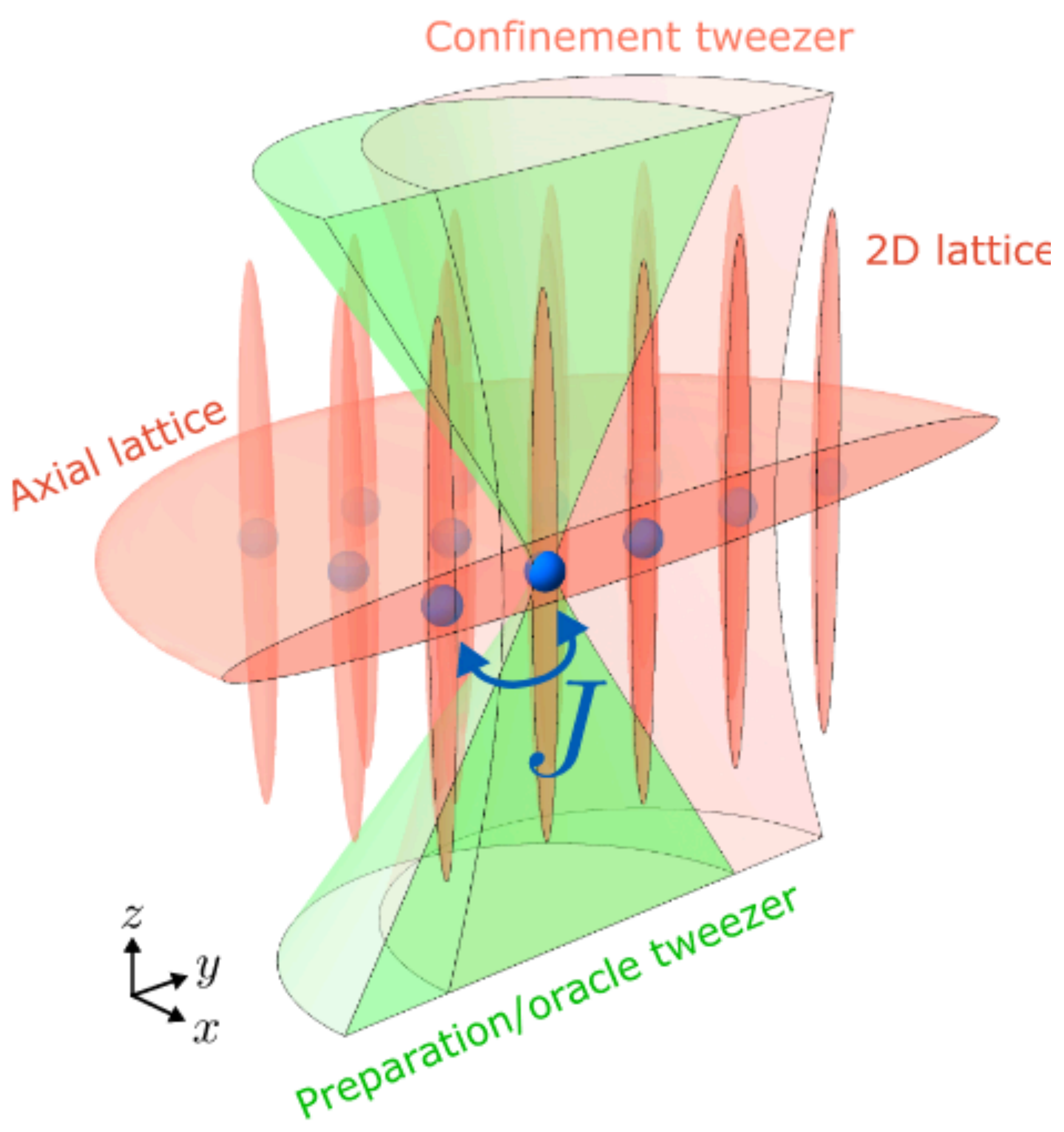

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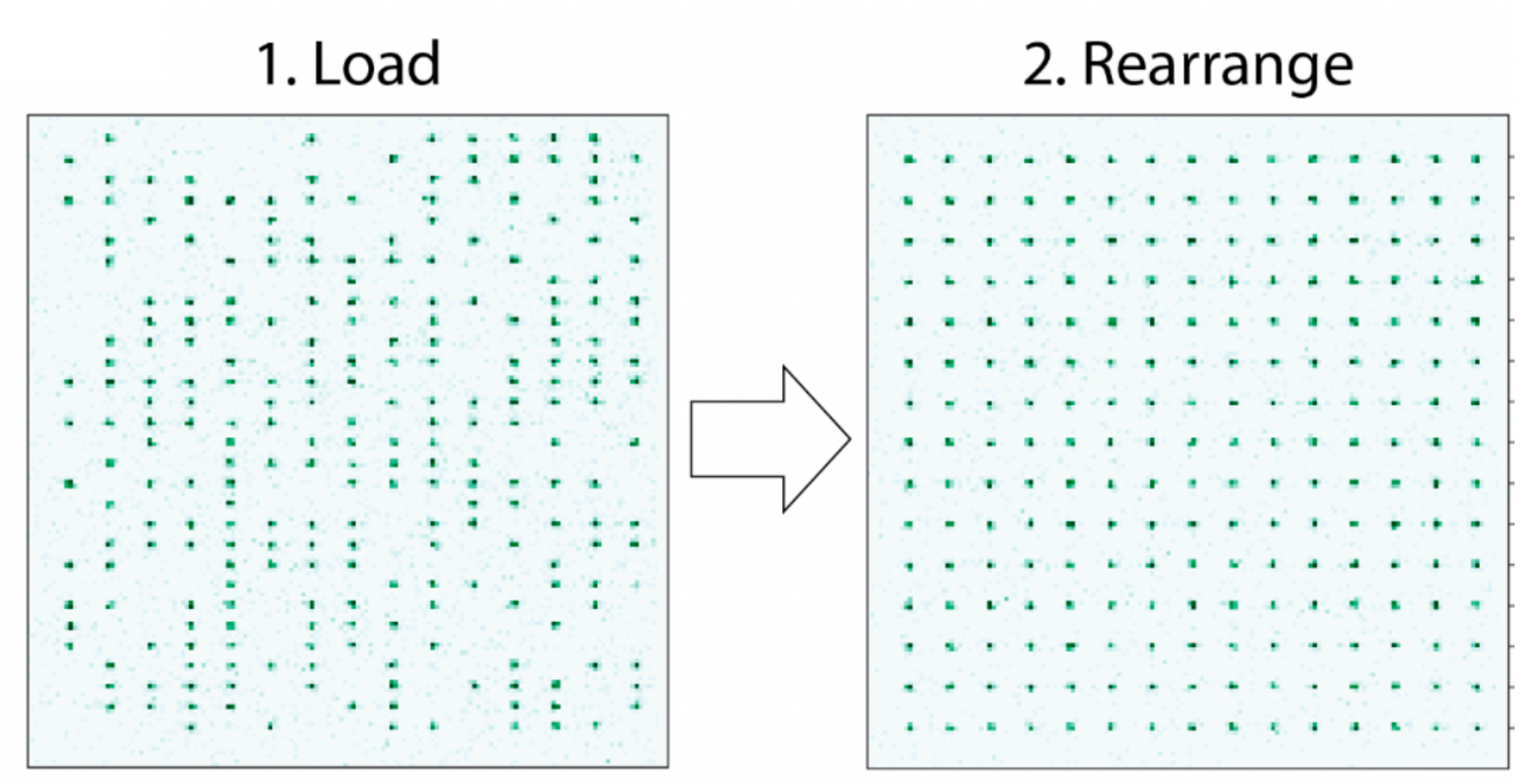

Ebadi, ..., Lukin, Nature **595**, 227 (2021)

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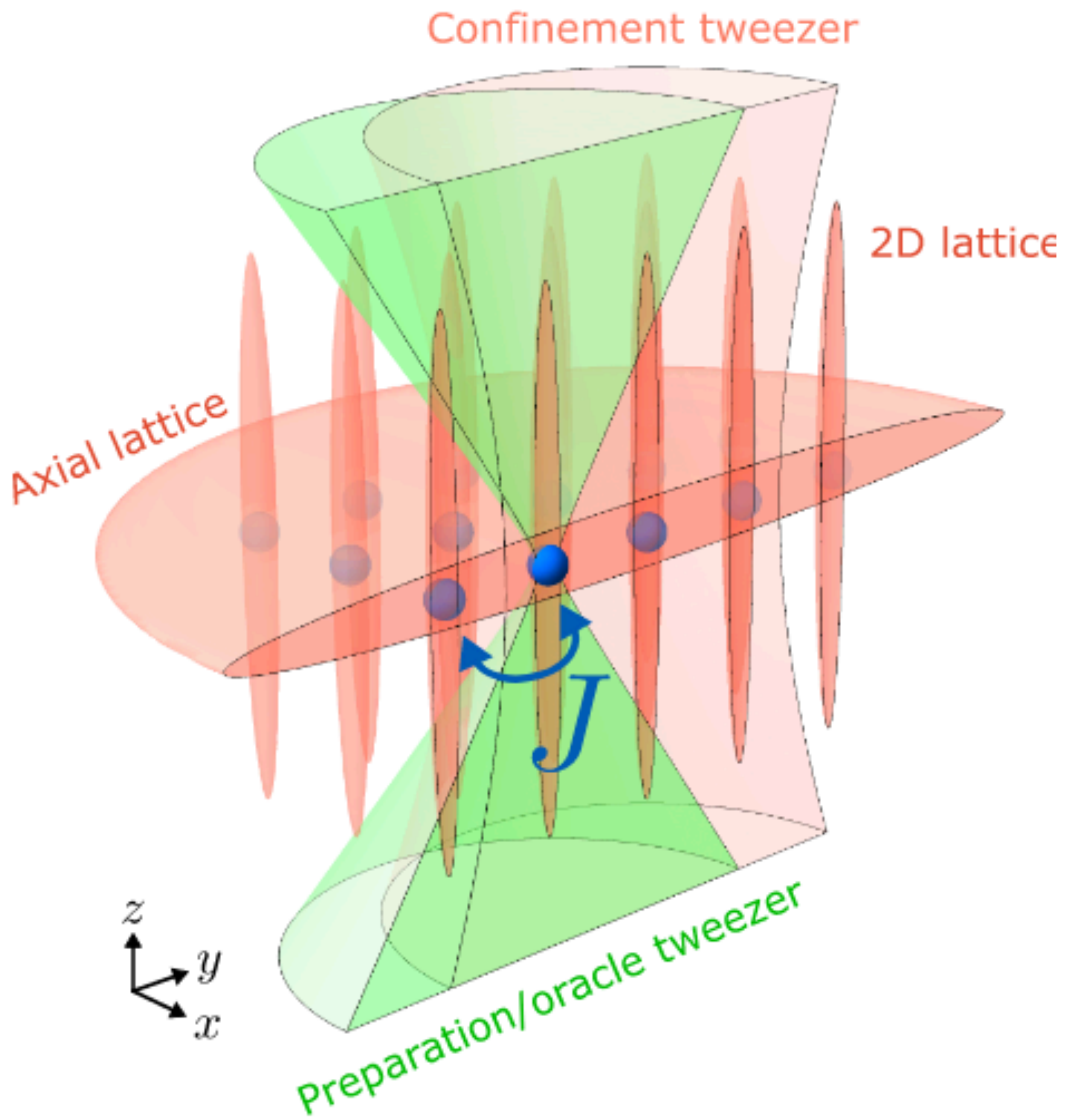

Programmable Bose-Hubbard system:
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Protocol for state preparation:

- Fast cycle times by direct laser cooling in deep optical traps
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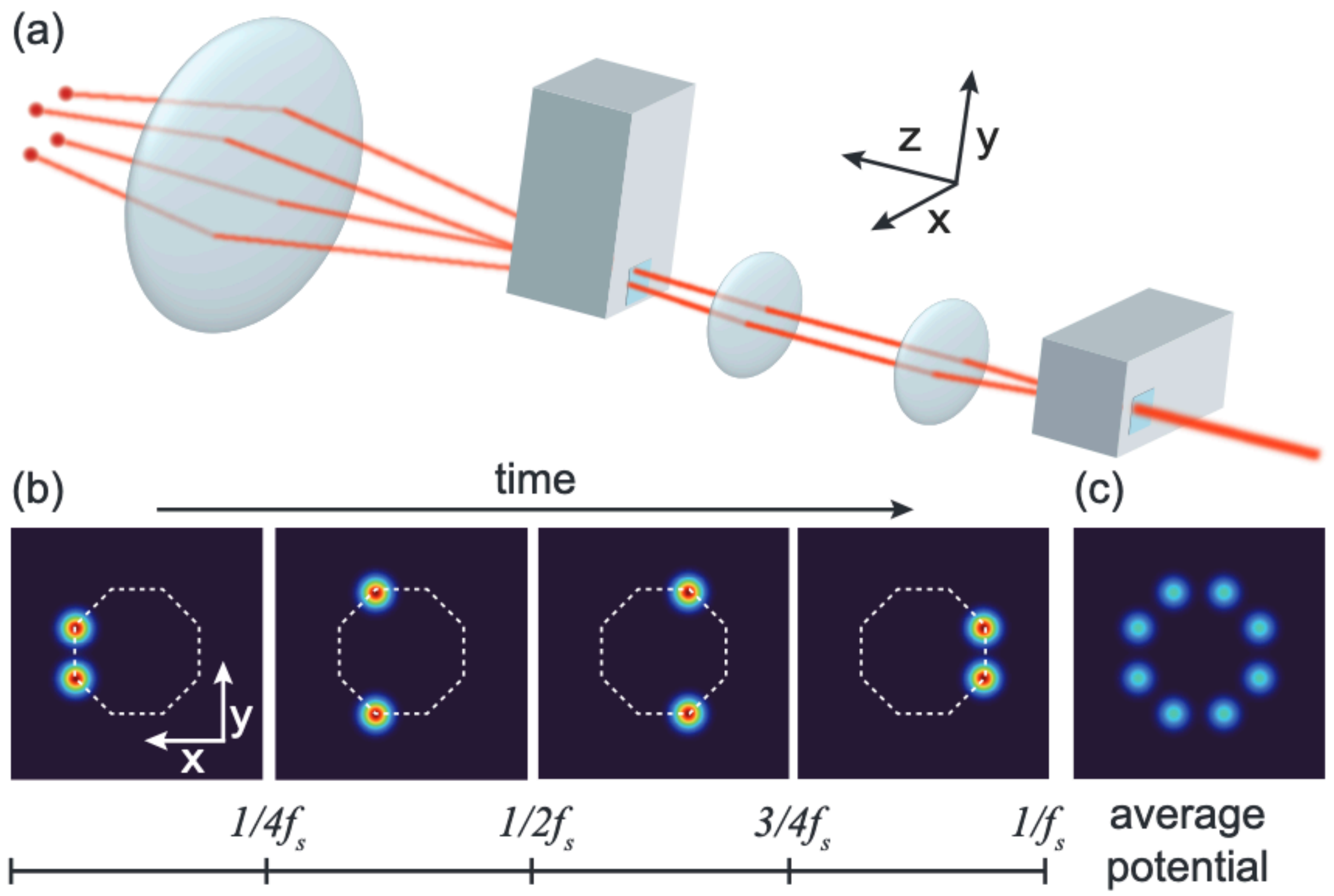
- Cycle time few 100ms
- Local manipulation of tunnel coupling in optical lattice

see also early work by C. Regal and more recently by W. Bakr, I. Bloch, J. Zeiher and Atom Computing

Other hybrid lattice-tweezer experiments

Programmable Fermi-Hubbard arrays



Z. Yan,..., W. Bakr, PRL **129**, 123201 (2022)

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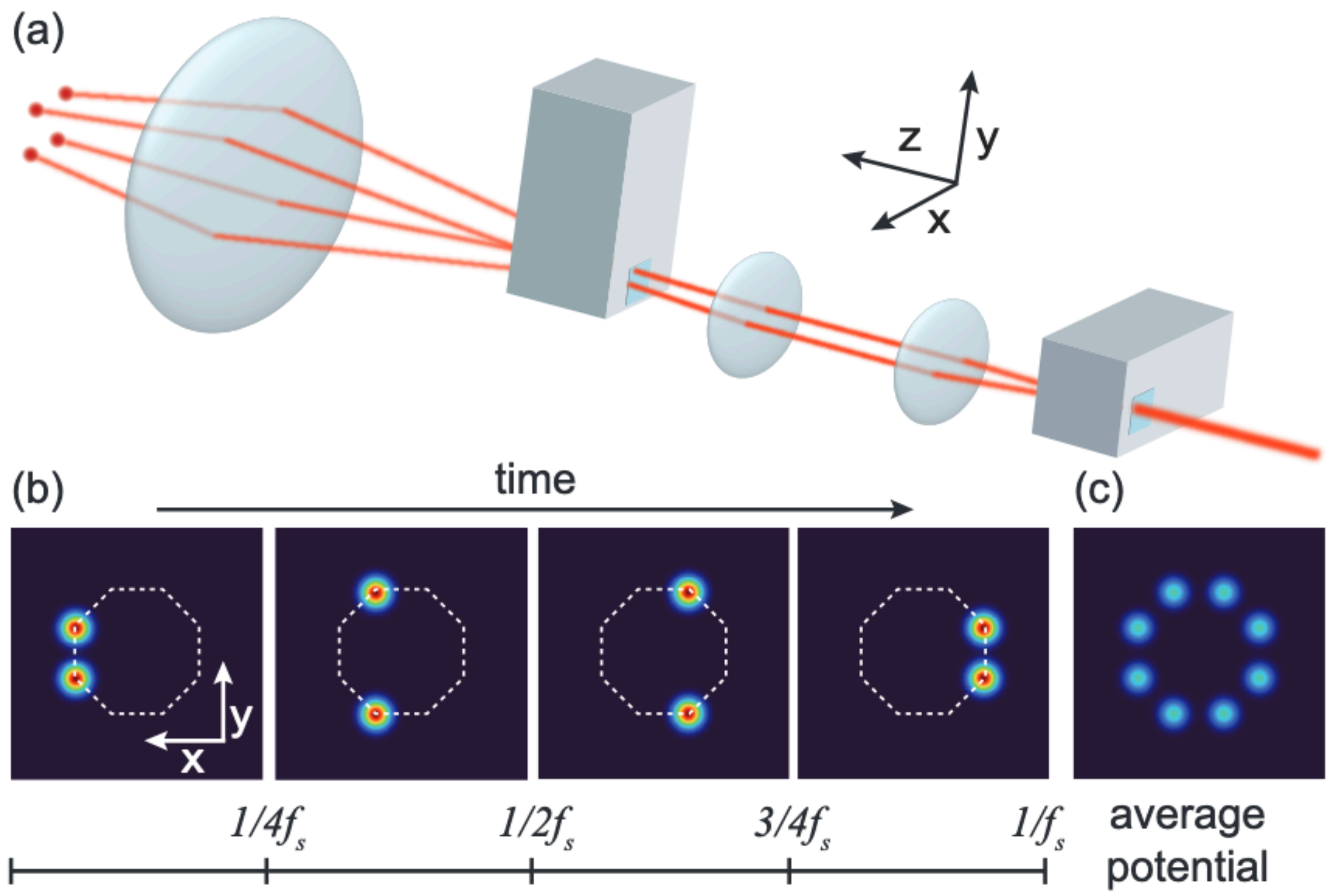
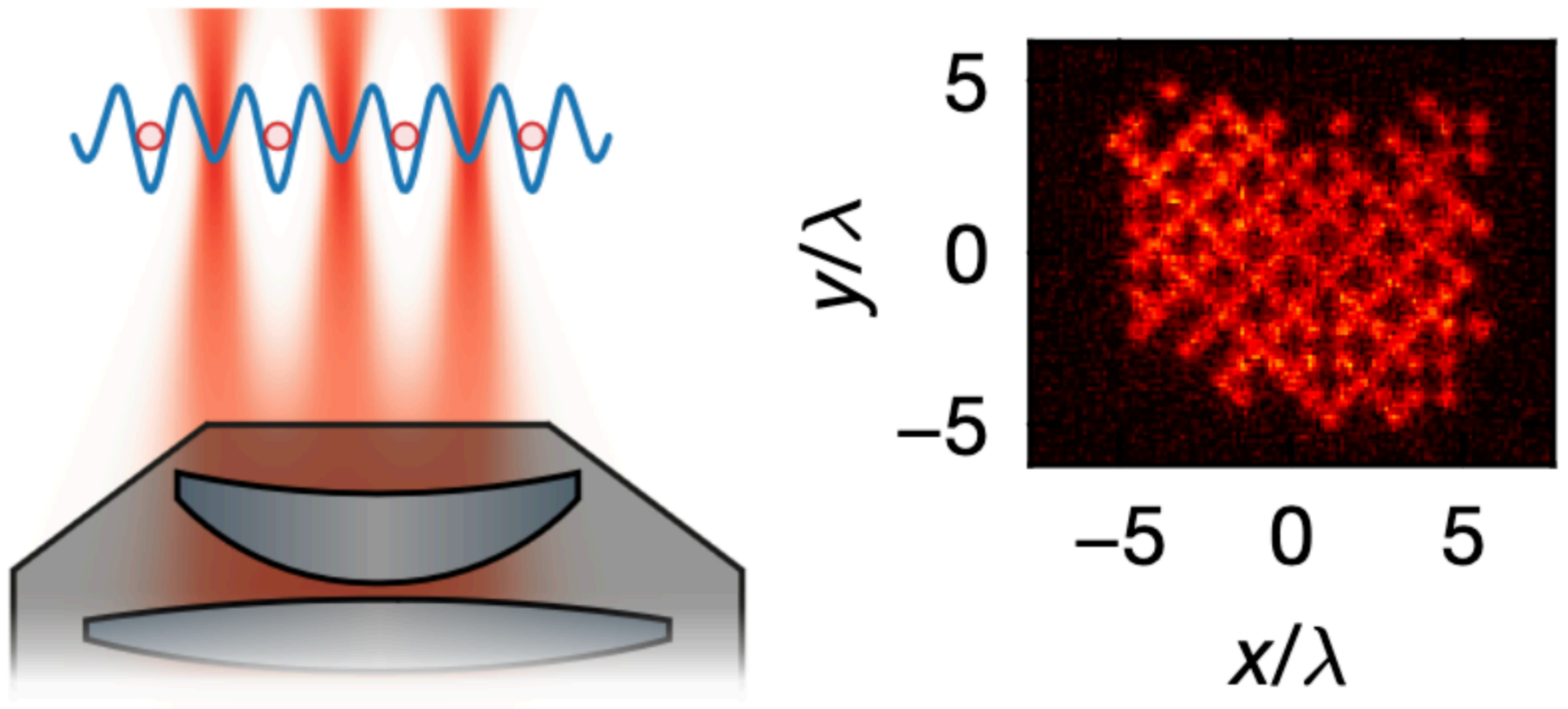


Z. Yan,..., W. Bakr, PRL **129**, 123201 (2022)

Programmable lattices in bosonic quantum gas microscope



Wei,..., Bloch, Zeiher, Phys. Rev. X **13**, 021042 (2023)

U(1) quantum link model in 2D with fermionic matter

U(1) lattice gauge theory in 1D

Quantum electrodynamics in 1D

lattice Schwinger model

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

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

w : nearest-neighbor tunneling

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

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m : mass of "positrons" and "electrons"

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

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

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Local charge:

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

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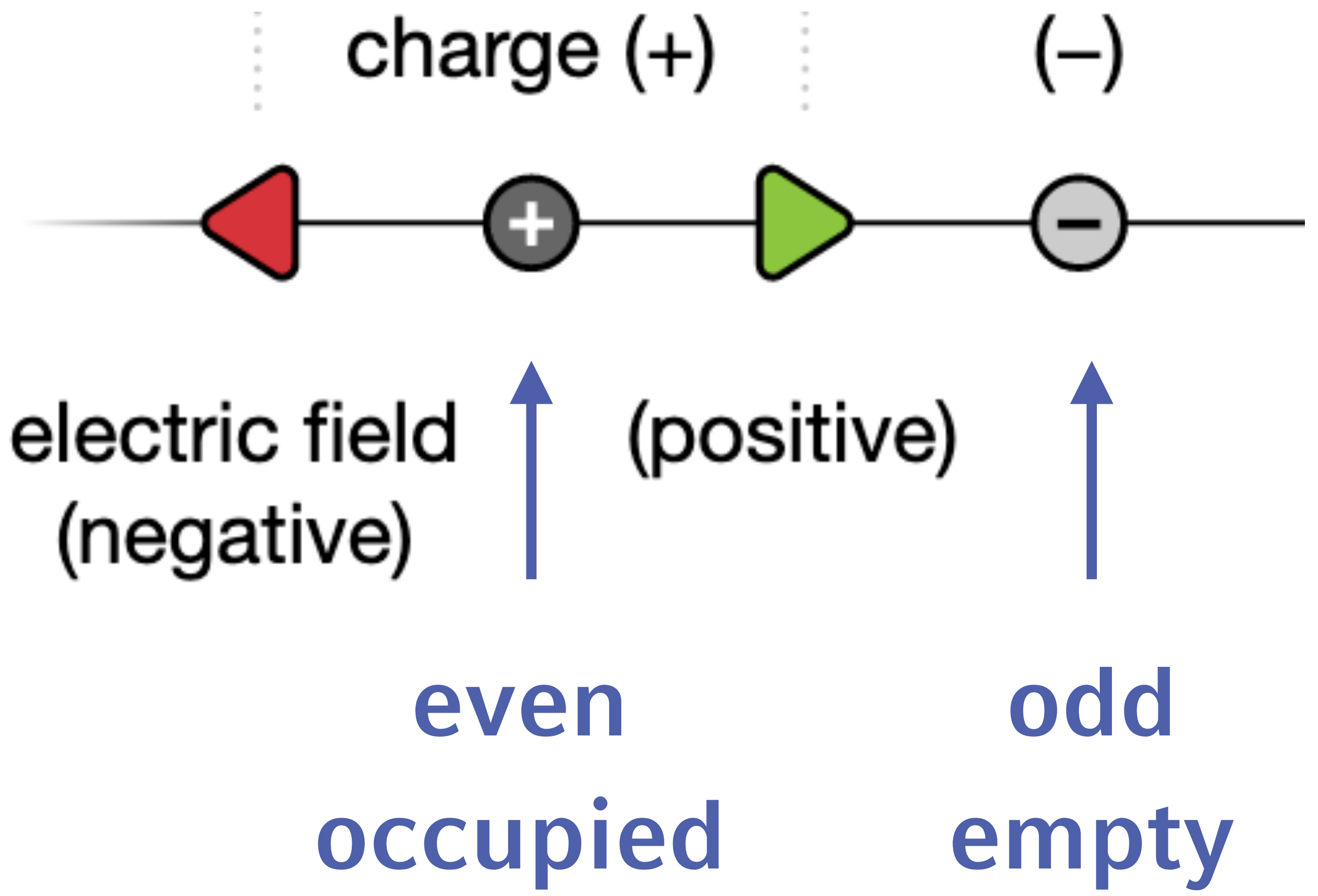

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Spin-1/2 quantum link model (QLM):

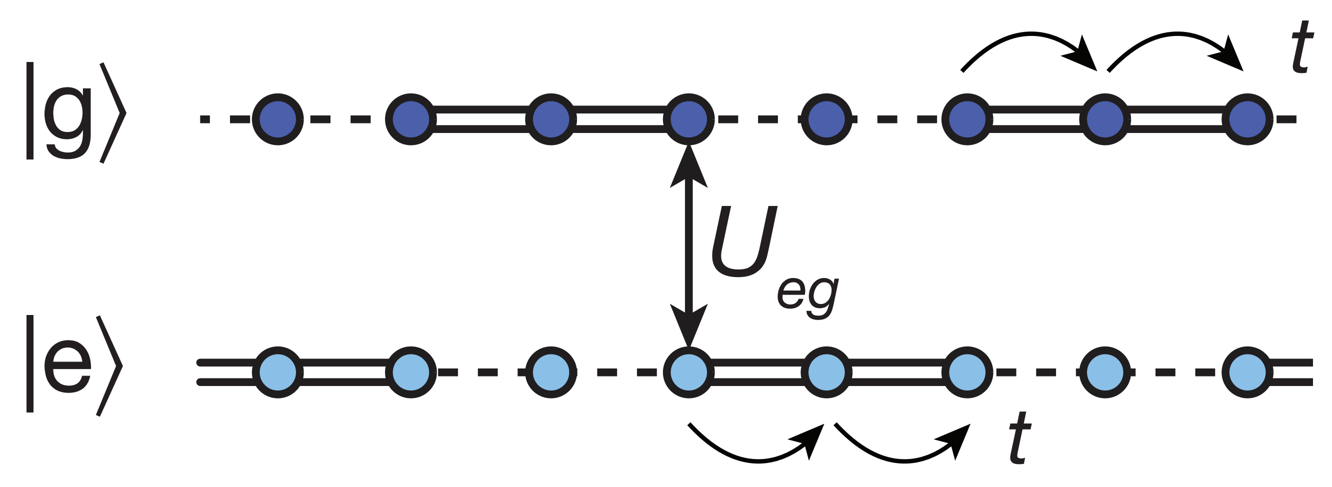
$$E_{j,j+1} \to S^z$$
$$U_{j,j+1} \to S^+$$

reduced Hilbert-space for link operators

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

The scheme

- State-dependent triple-well lattice



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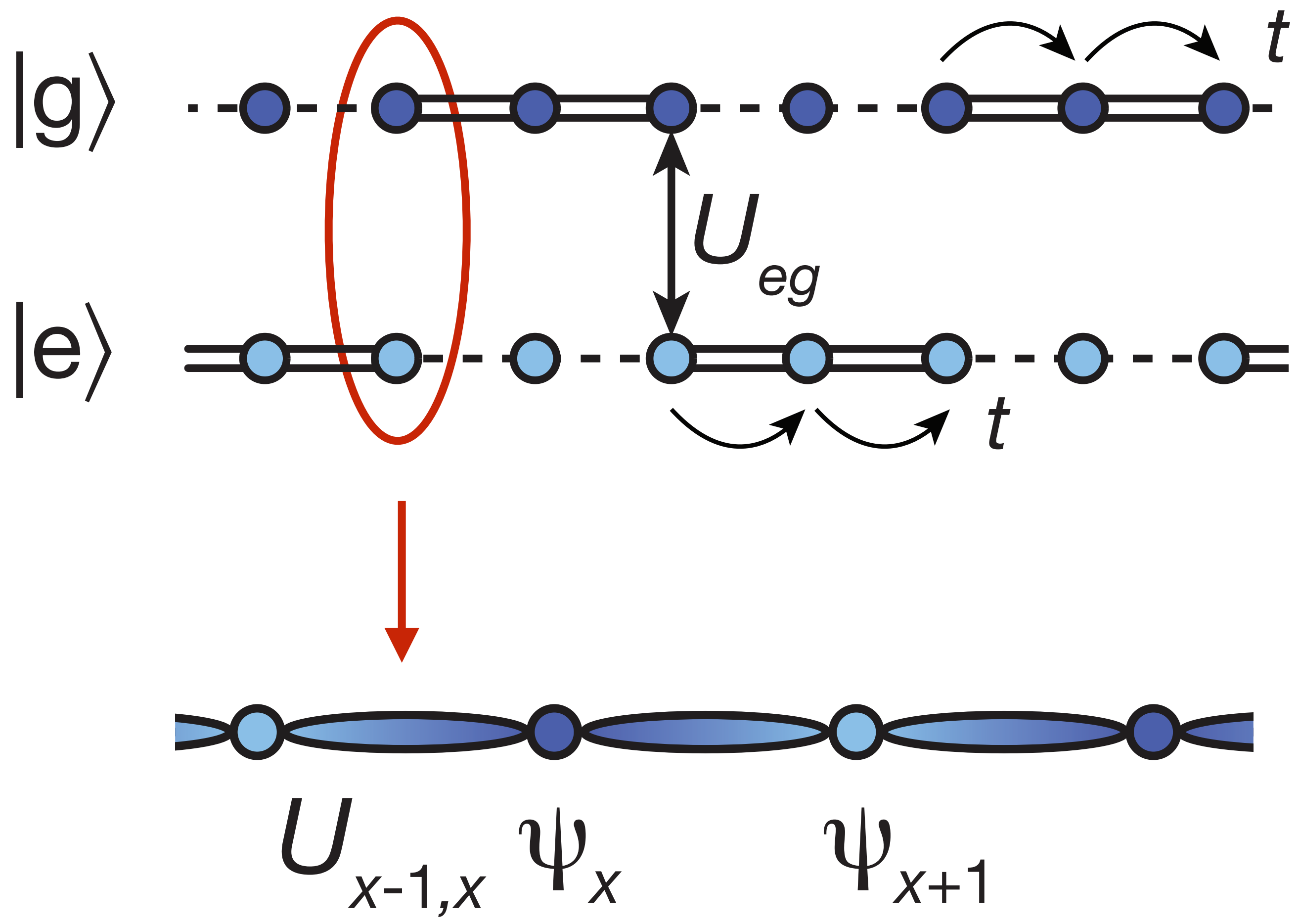
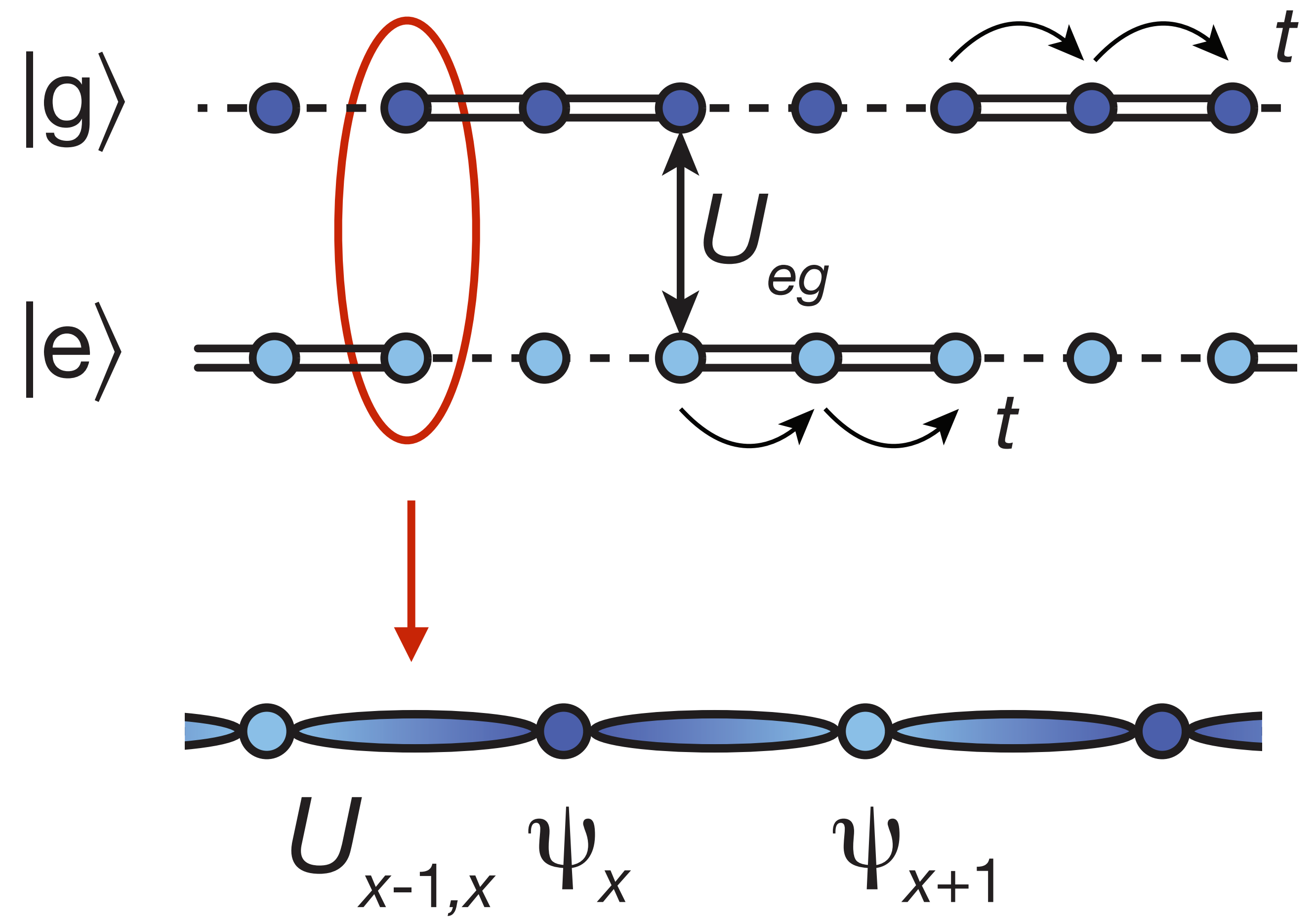


S=1/2 quantum link model

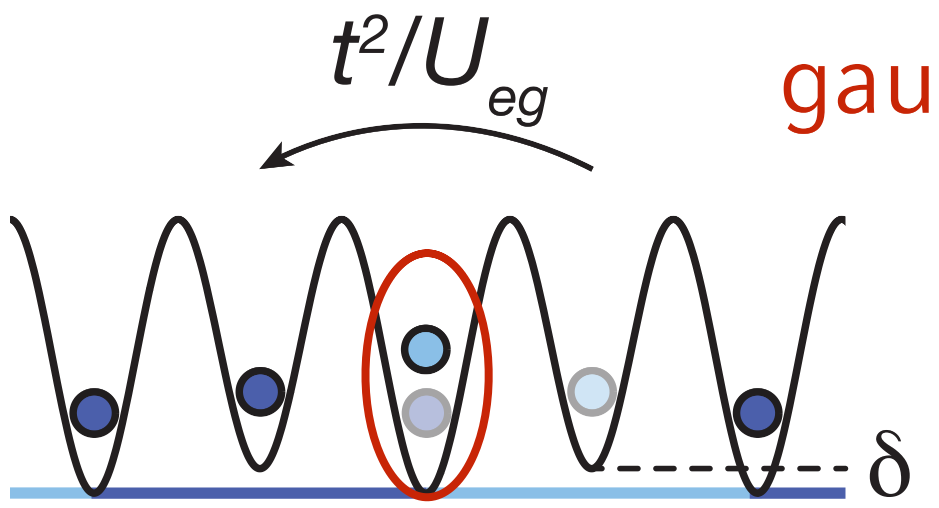
The scheme

- State-dependent triple-well lattice



S=1/2 quantum link model

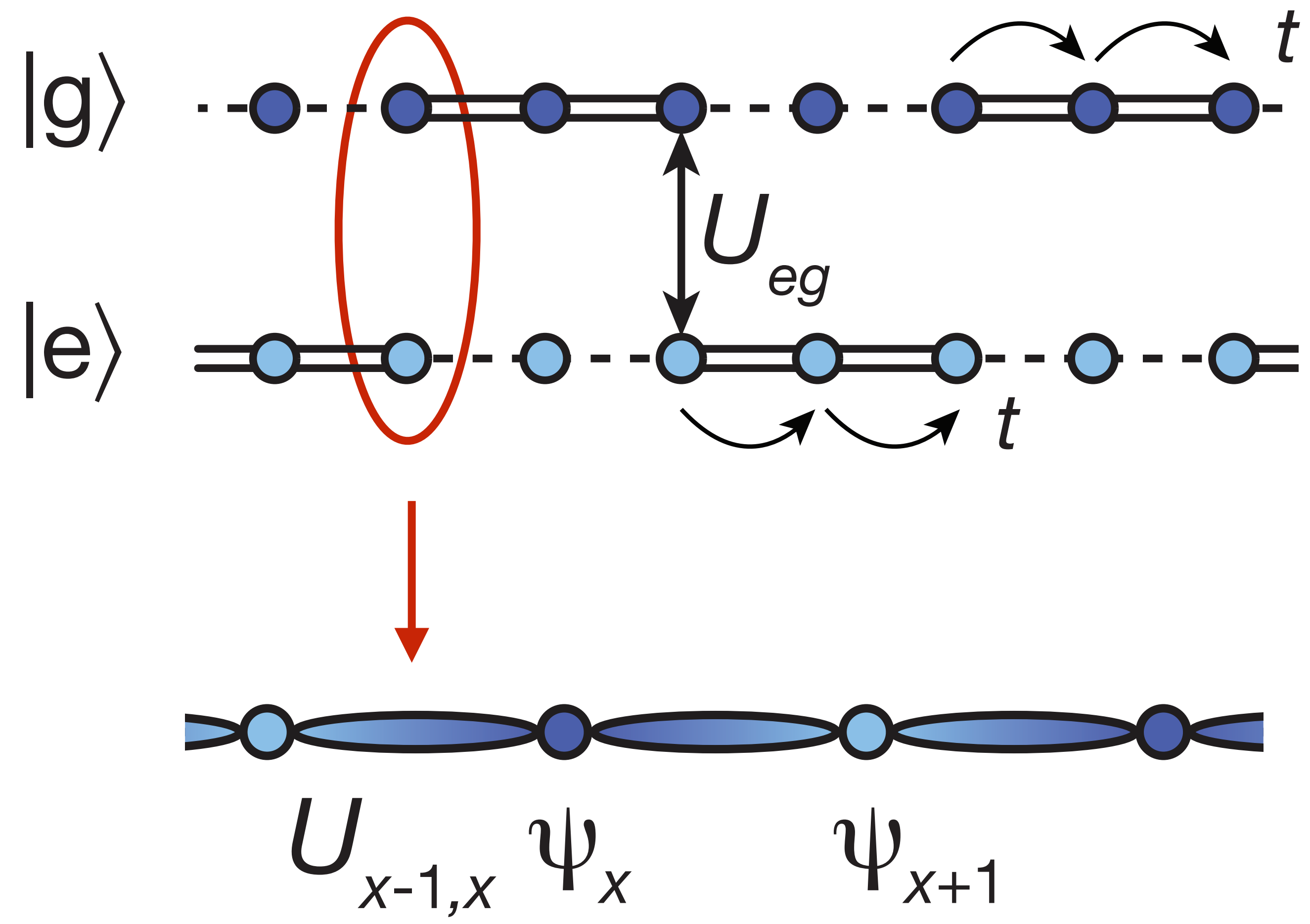
- *Building block:* correlated hopping of fermions



gauge field

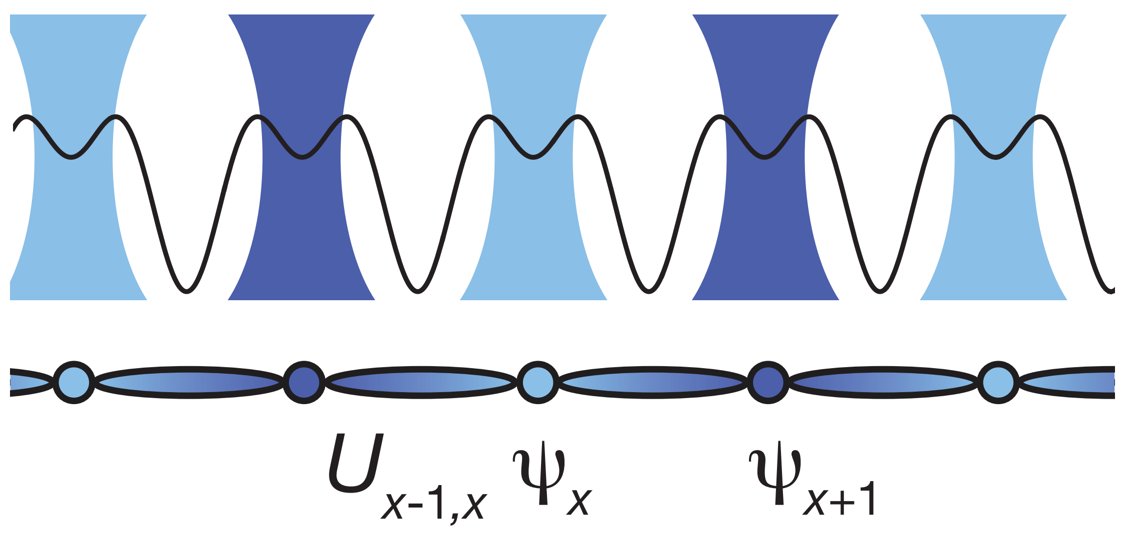
The scheme

- State-dependent triple-well lattice



S=1/2 quantum link model

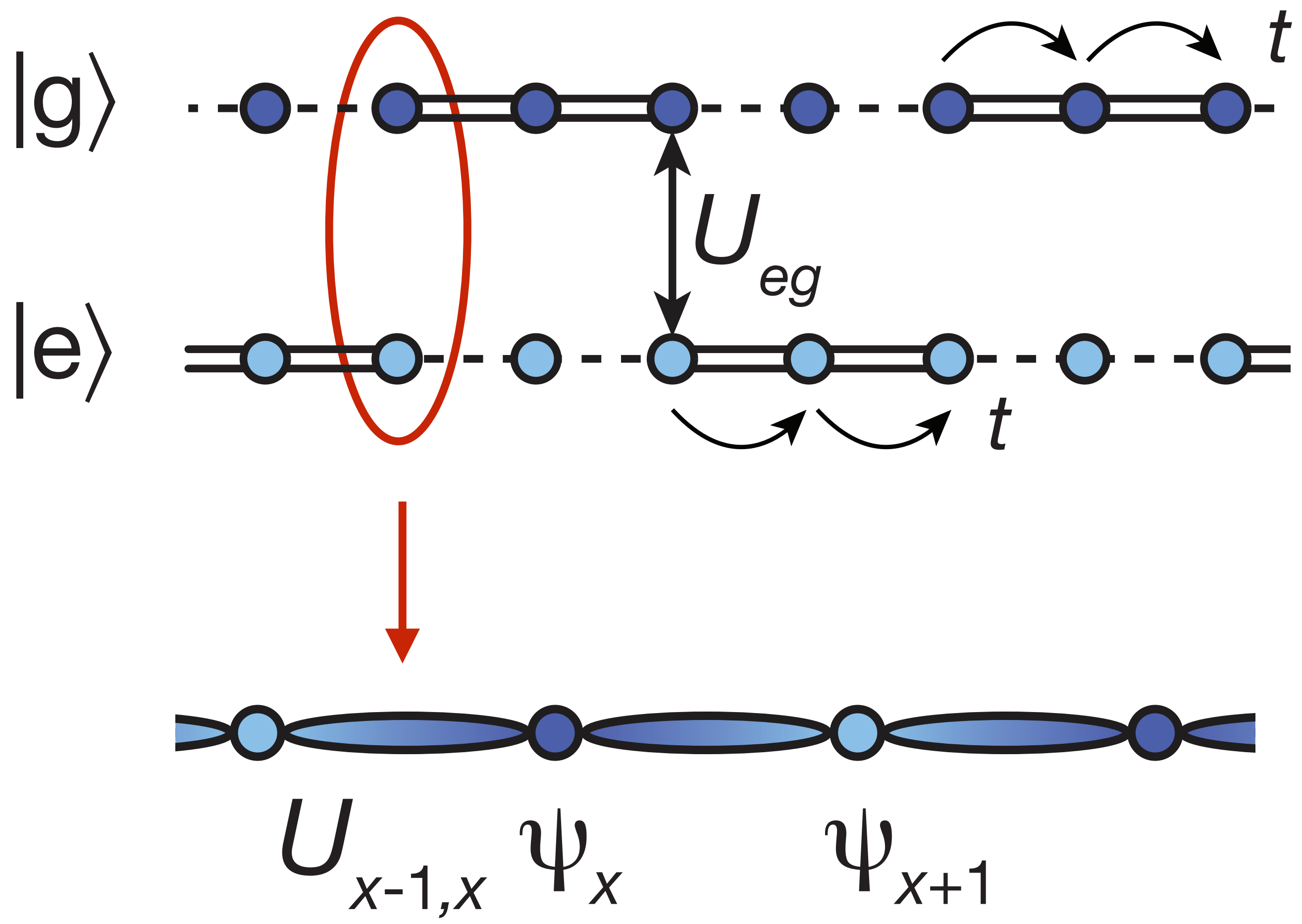
- Implementation:



state-dependent addressing

The scheme

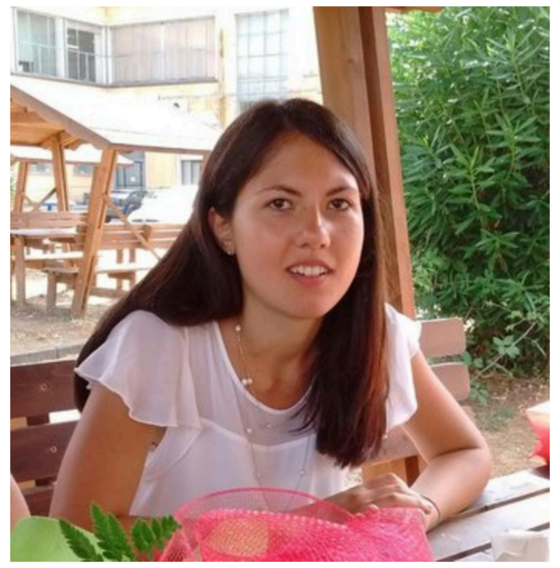
- State-dependent triple-well lattice



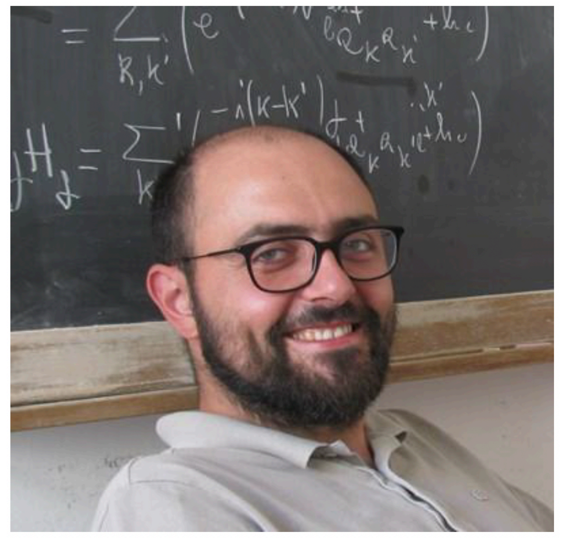
S=1/2 quantum link model

- **Ab initio calculations:**


N. Darwah Oppong

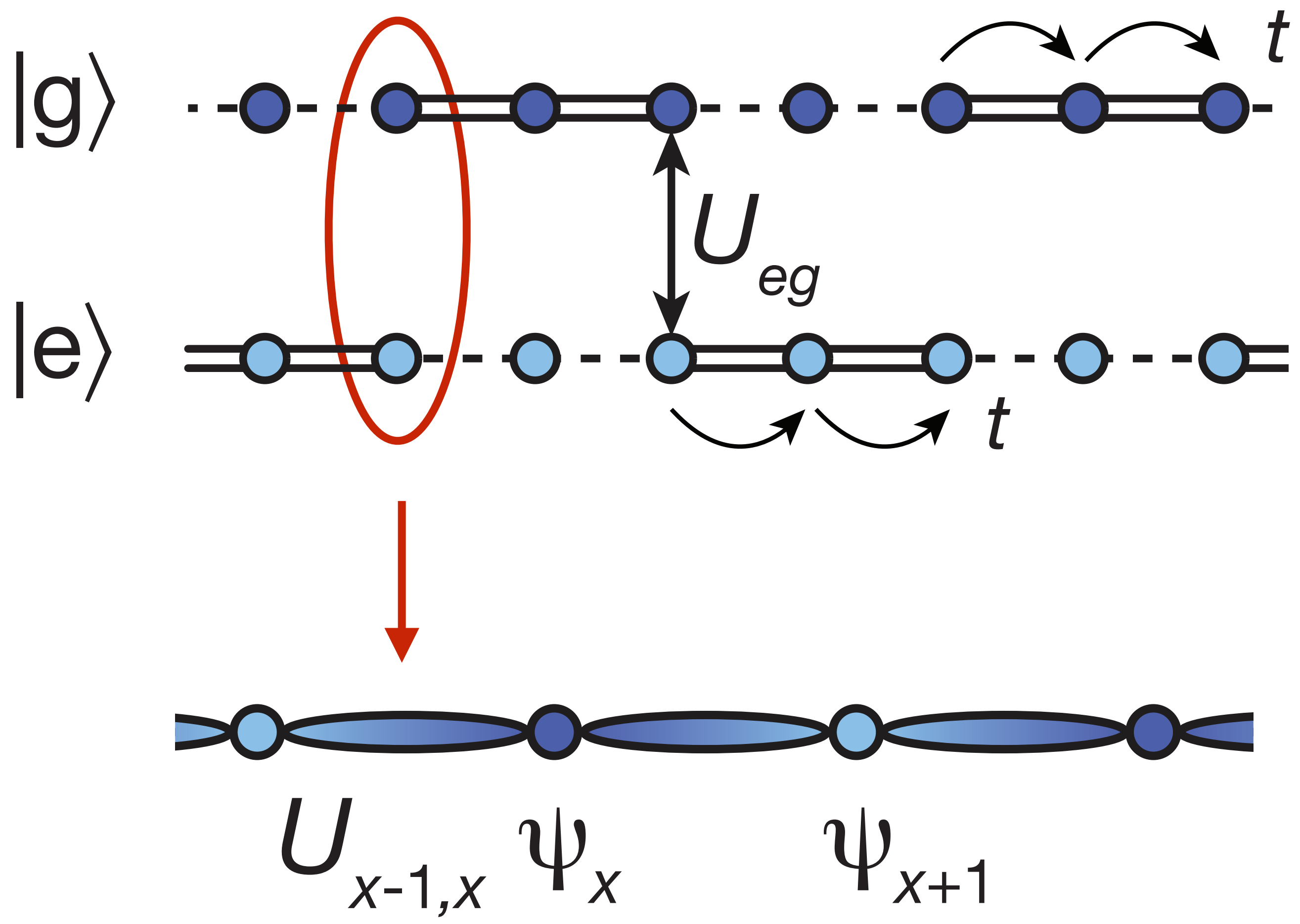

F. Surace


P. Fromholz


M. Dalmonte

The scheme

- State-dependent triple-well lattice



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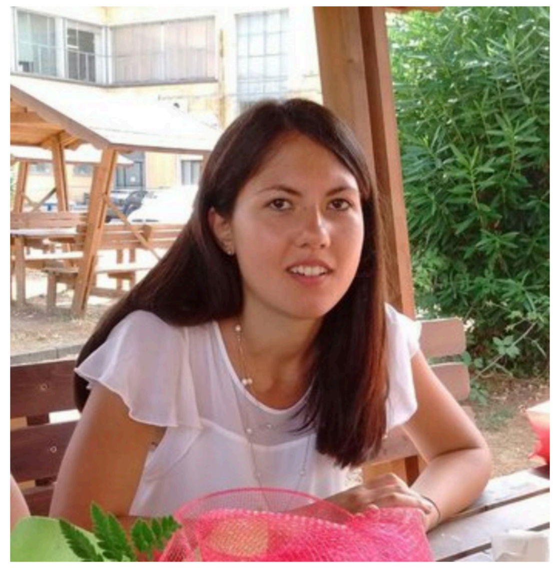

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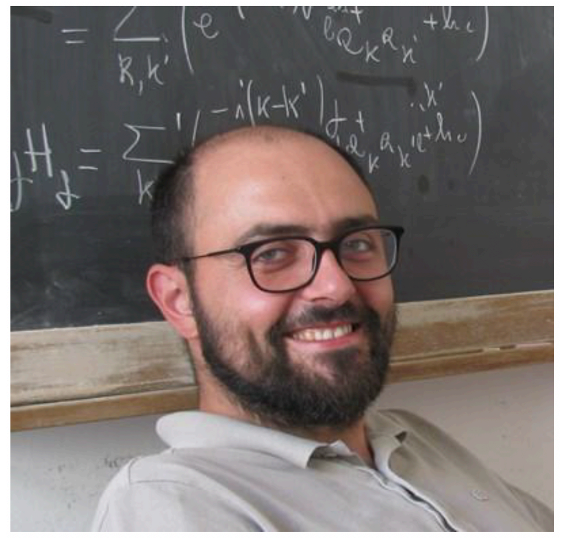


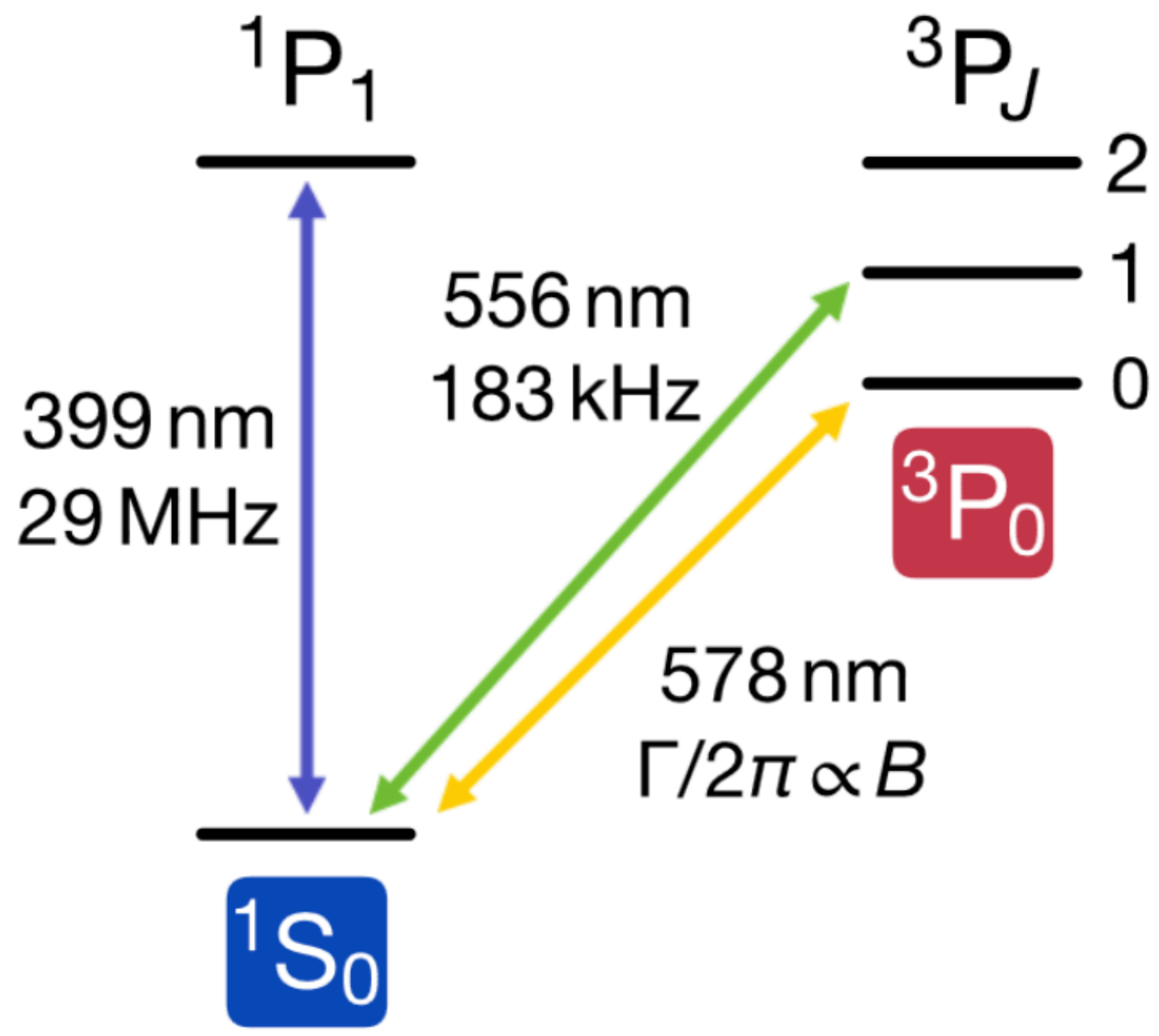
M. Dalmonte

Surace, Fromholz, Darkwah Oppong, Dalmonte, Aidelsburger, PRX Quantum **4**, 020330 (2023)

Quantum simulation with Yb atoms
- experimental setup

Simplified level scheme

Yb atoms:



- Long-lived clock state enables engineering of novel model Hamiltonians ↔ mixtures

Simplified level scheme

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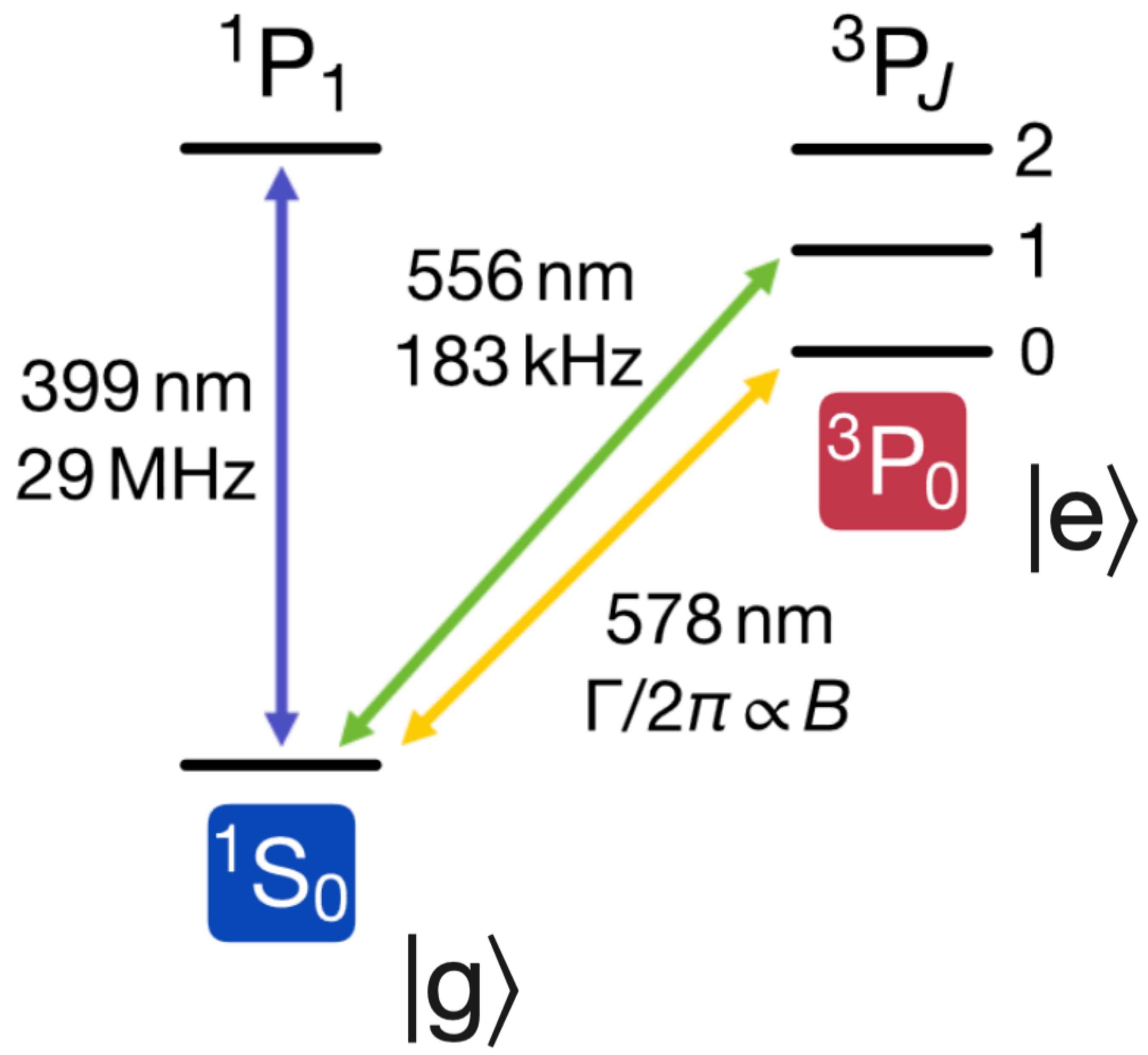

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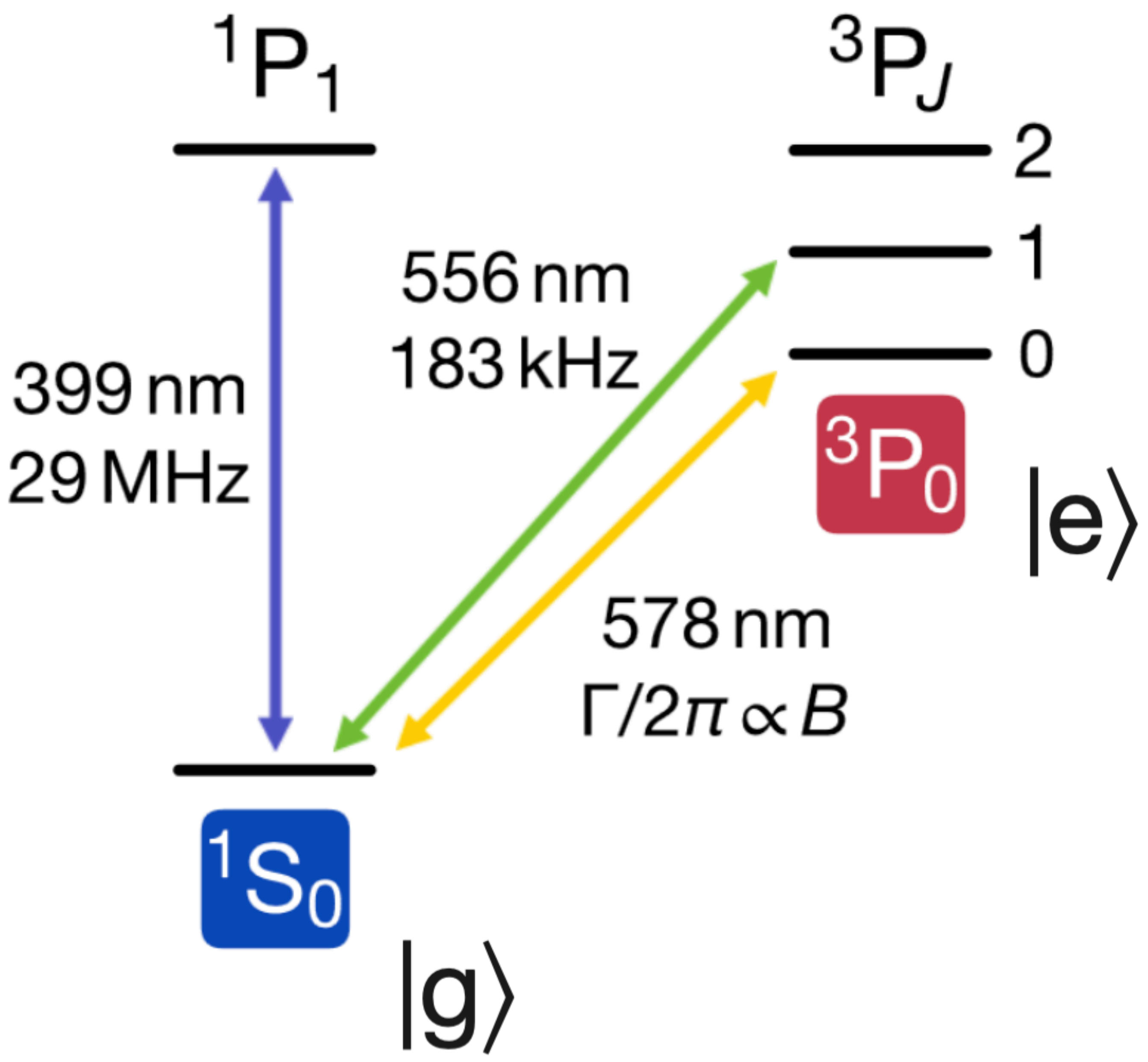

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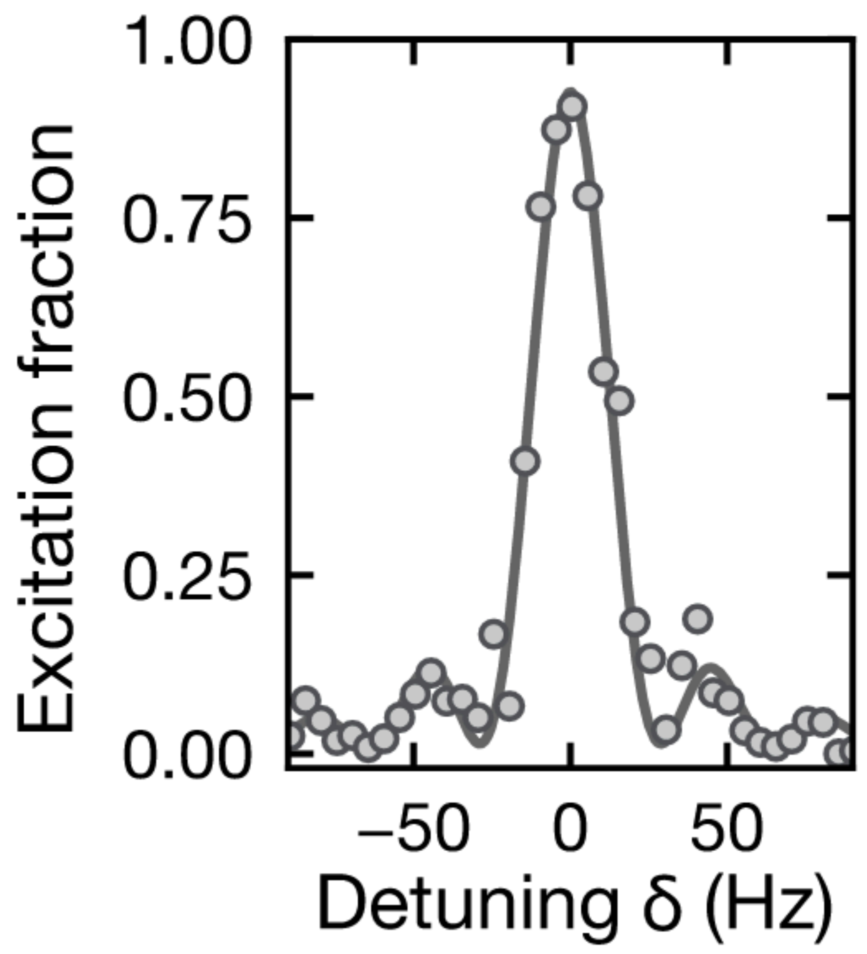
- High-resolution spectroscopy on clock transition

  Kolkowitz,...,Ye,
  Nature **542**, 66 (2017)



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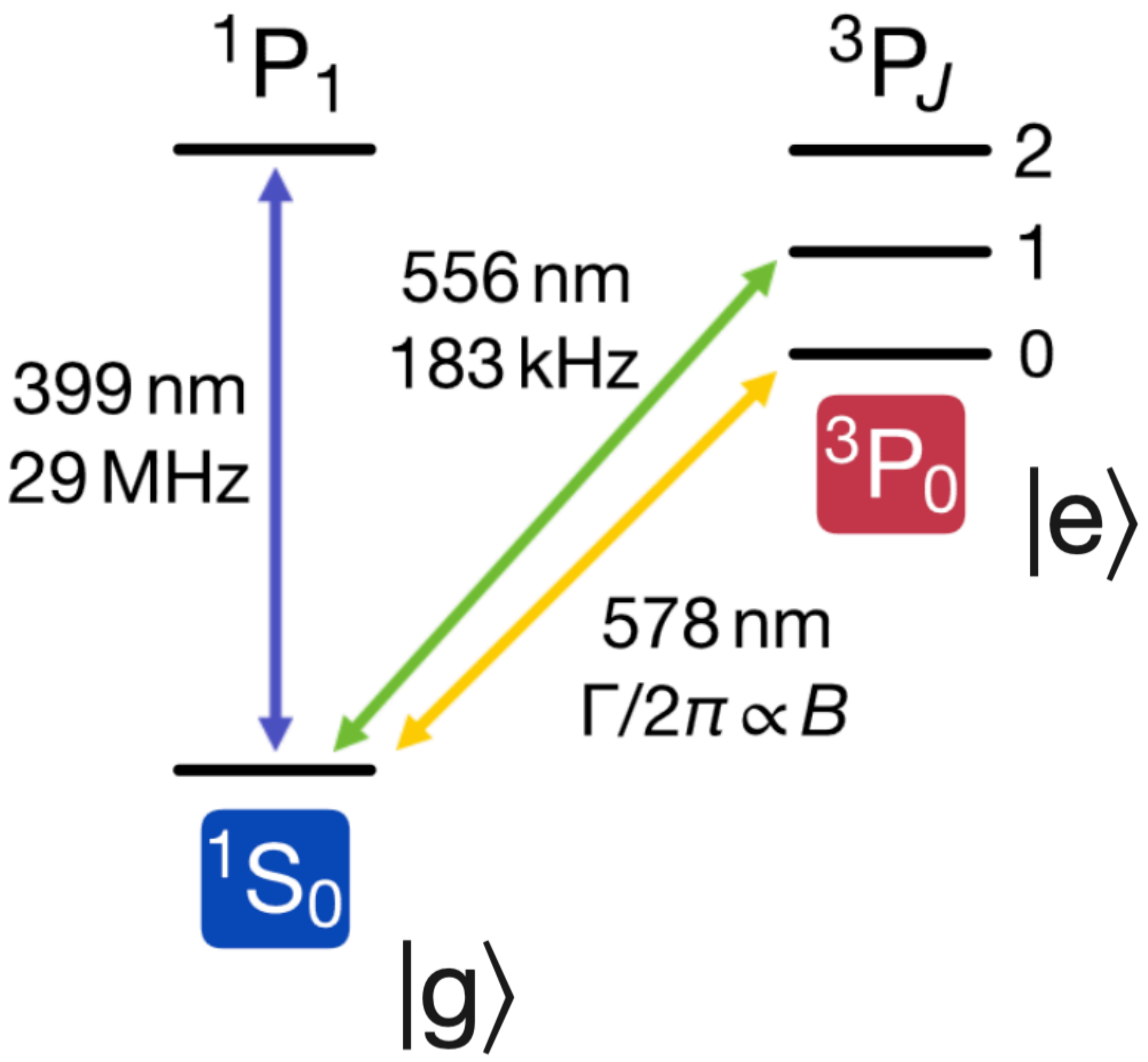

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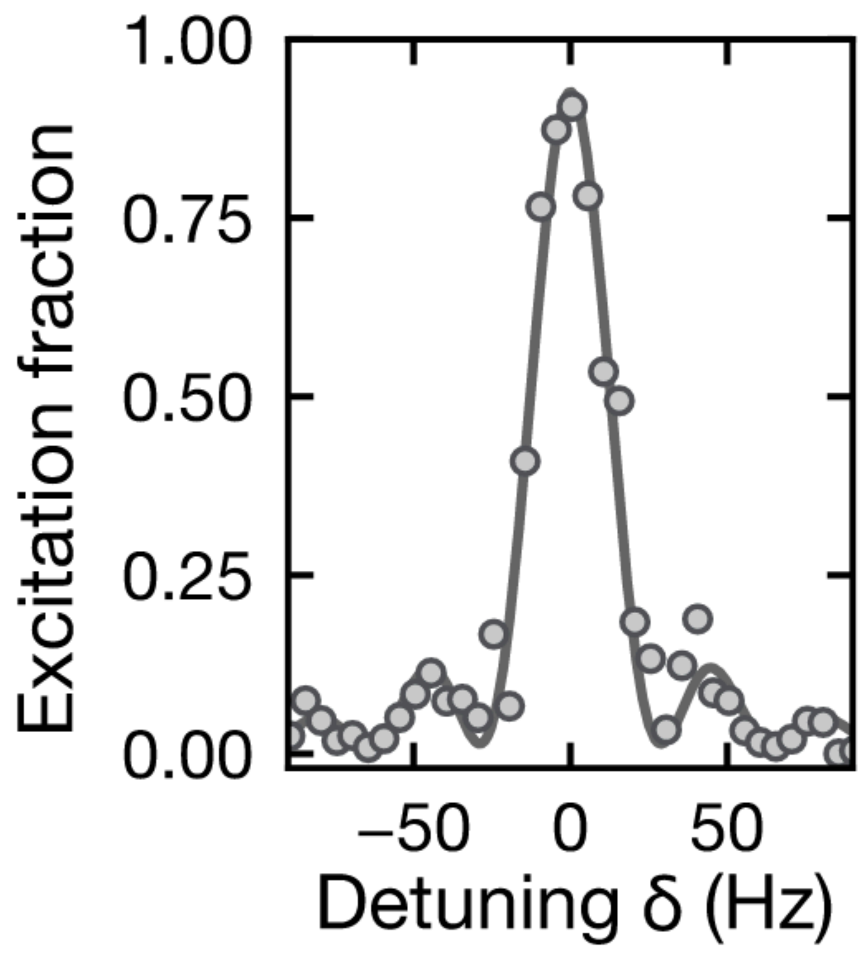
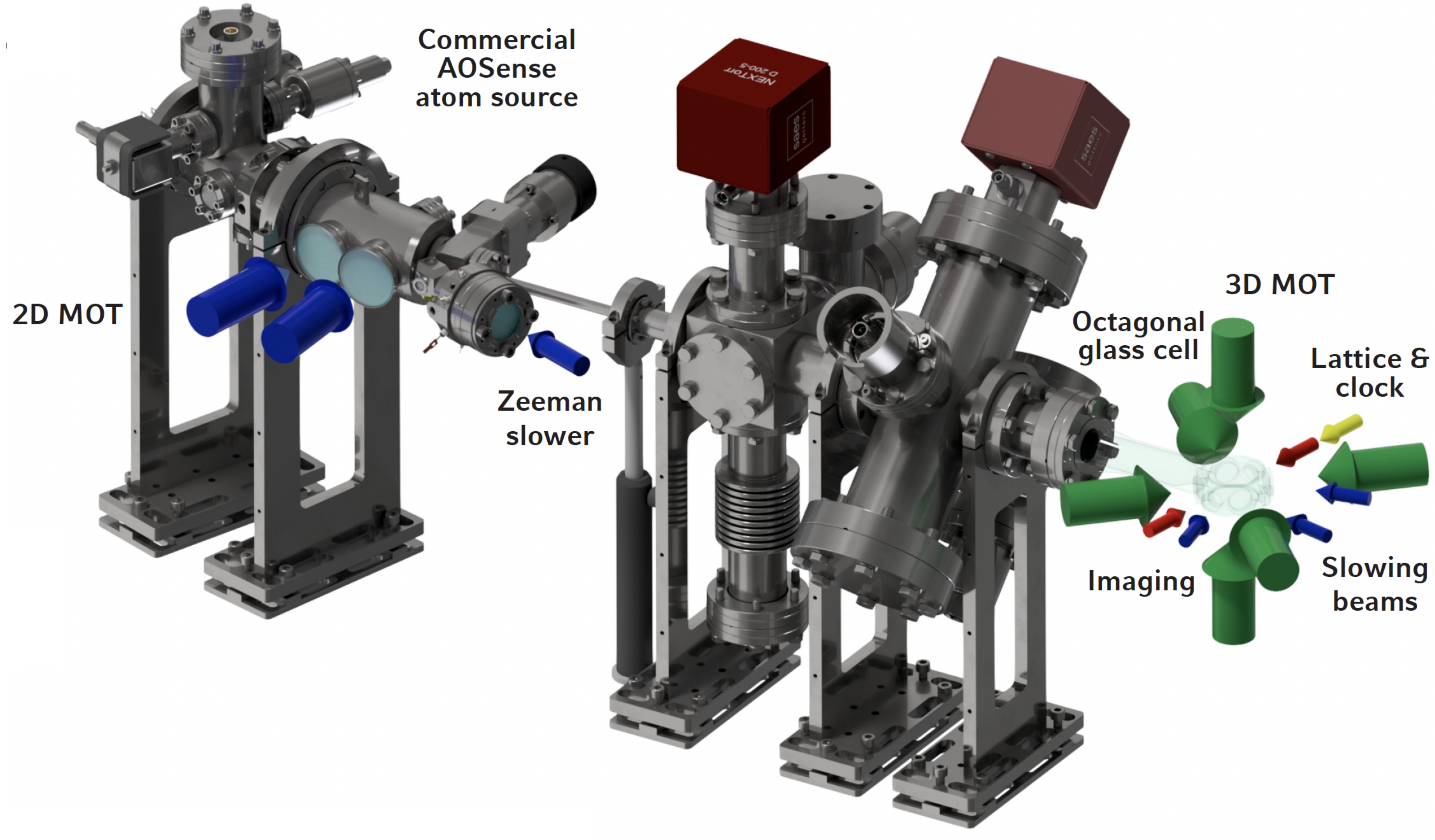


- State-dependent potentials with low heating

Riegger,...,Fölling, PRL 120, 143601 (2018); Darkwah Oppong,...,Fölling, PRX 12, 031026 (2022), Heinz,...,Blatt, PRL 124, 203201 (2020)

Experimental setup



Höhn, Staub, Brochier, Darkwah Oppong, Aidelsburger, Phys. Rev. A **108**, 053325 (2023)

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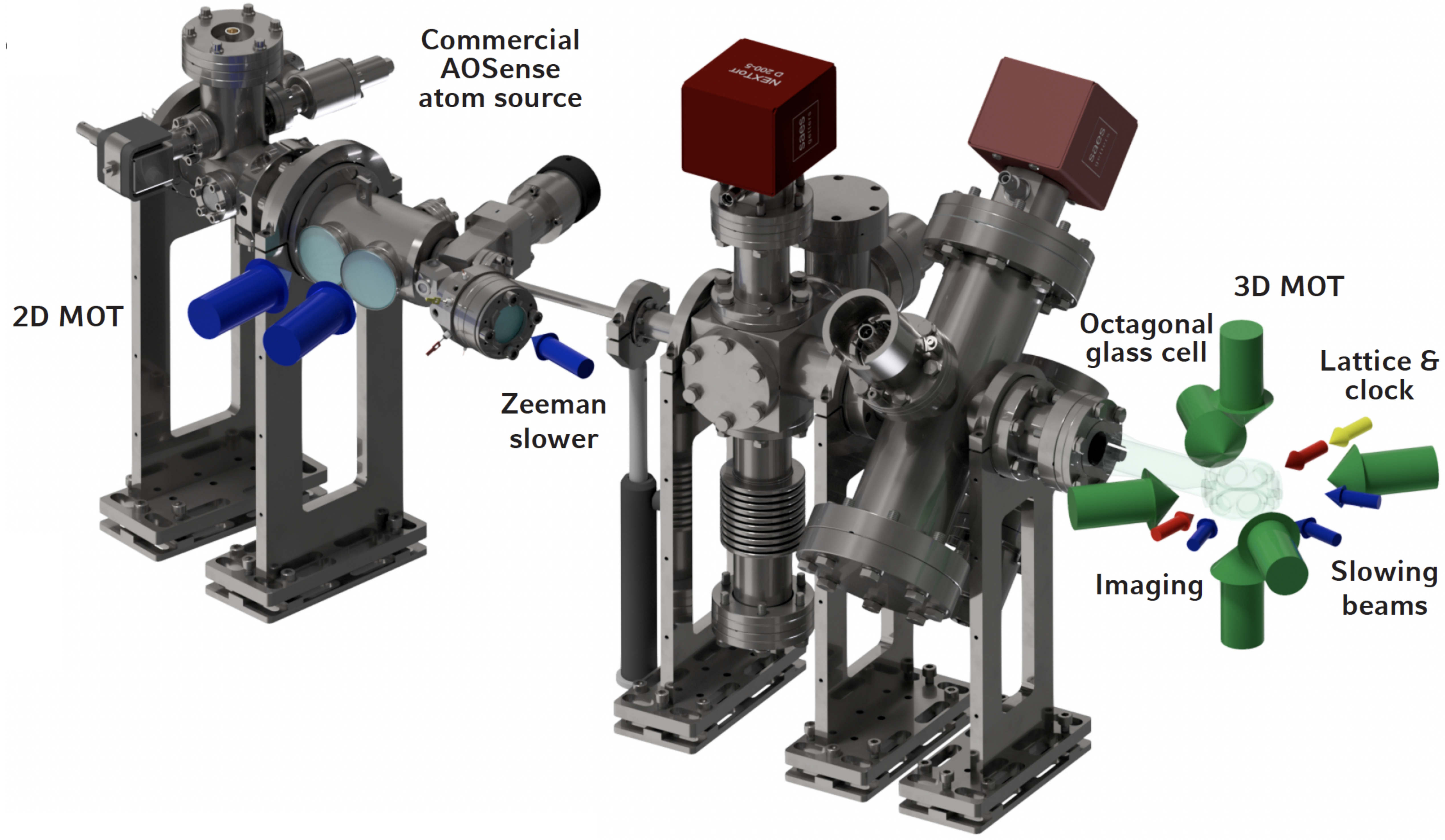
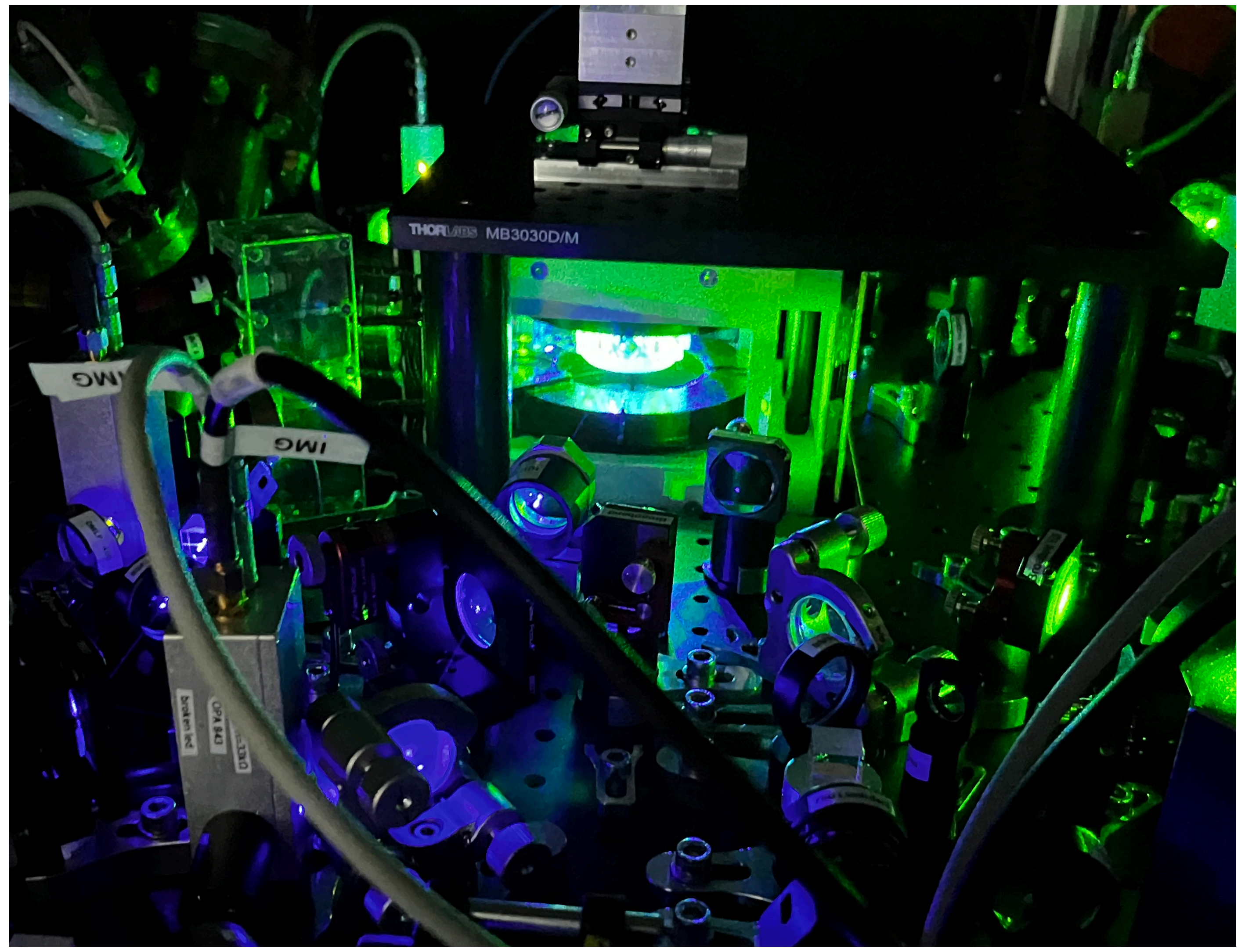


^{171}Yb & ^{174}Yb MOT

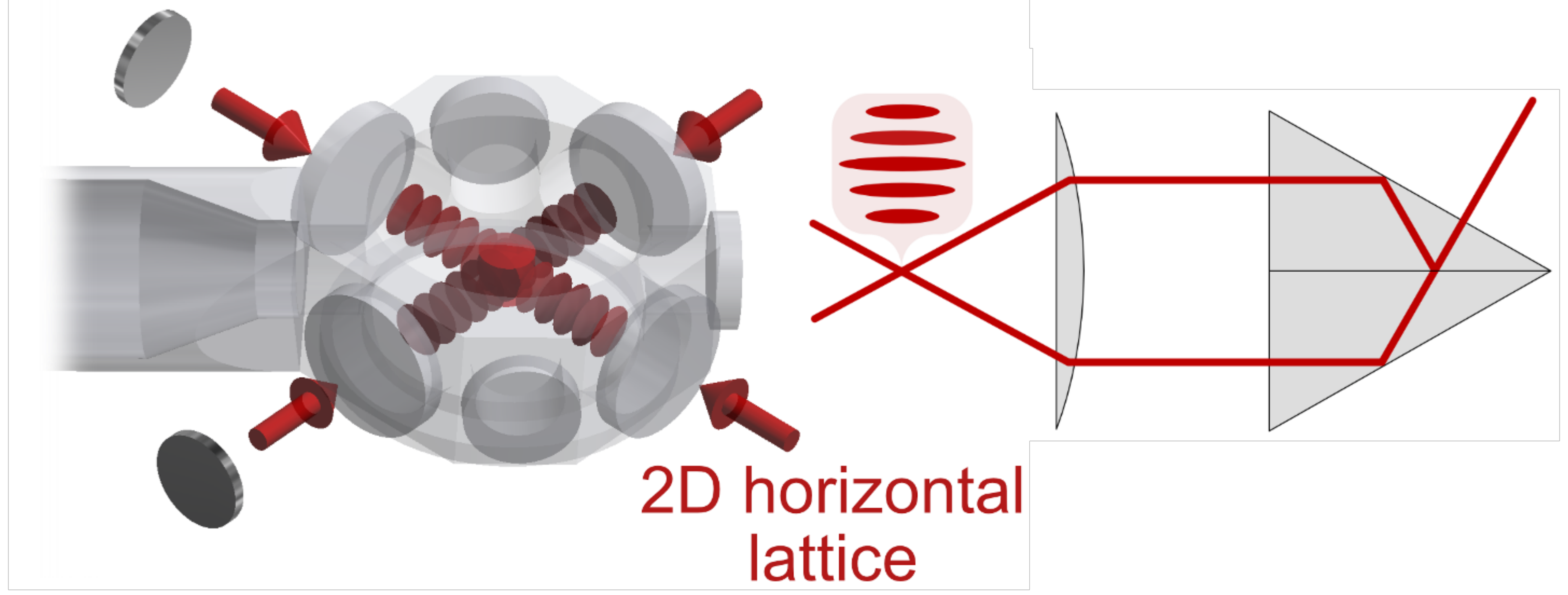


Bosonic & fermionic MOT

Höhn, Staub, Brochier, Darkwah Oppong, Aidelsburger, Phys. Rev. A **108**, 053325 (2023)

Current status of the experimental setup

3D magic-wavelength lattice



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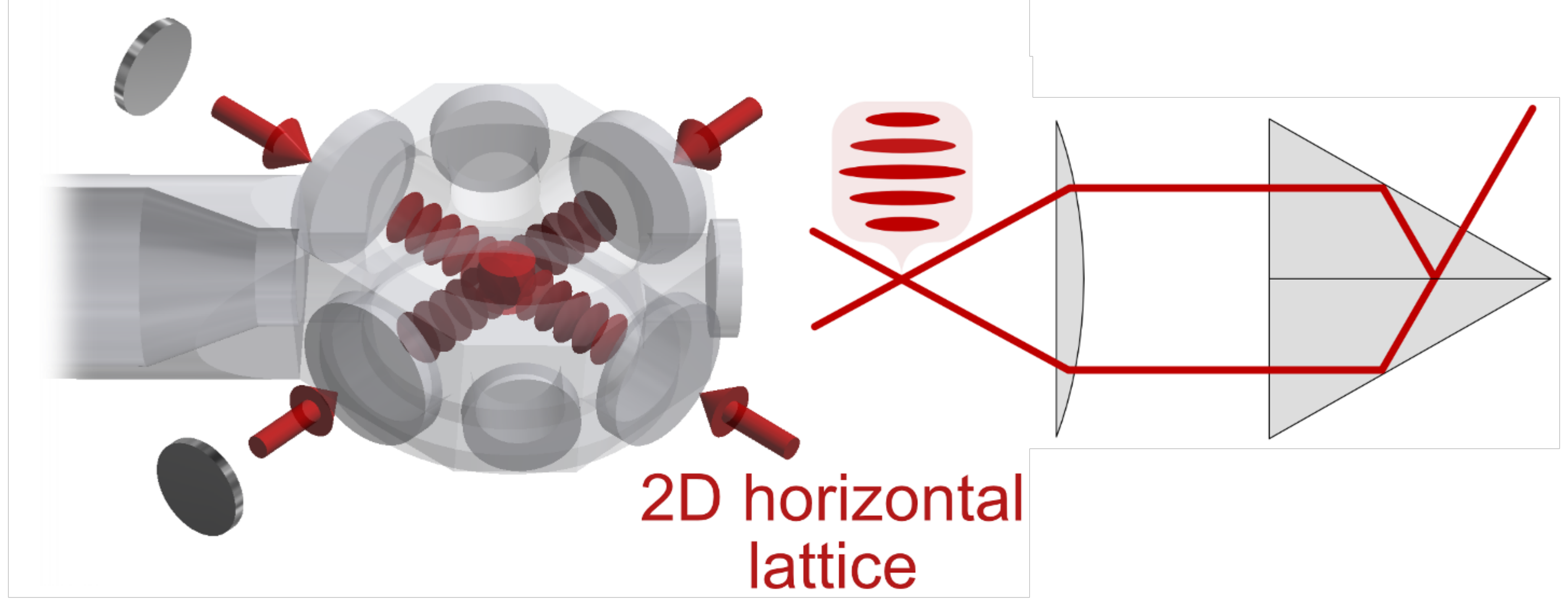

- 2D square lattice
- Vertical confinement: Lattice formed with Kösters prism

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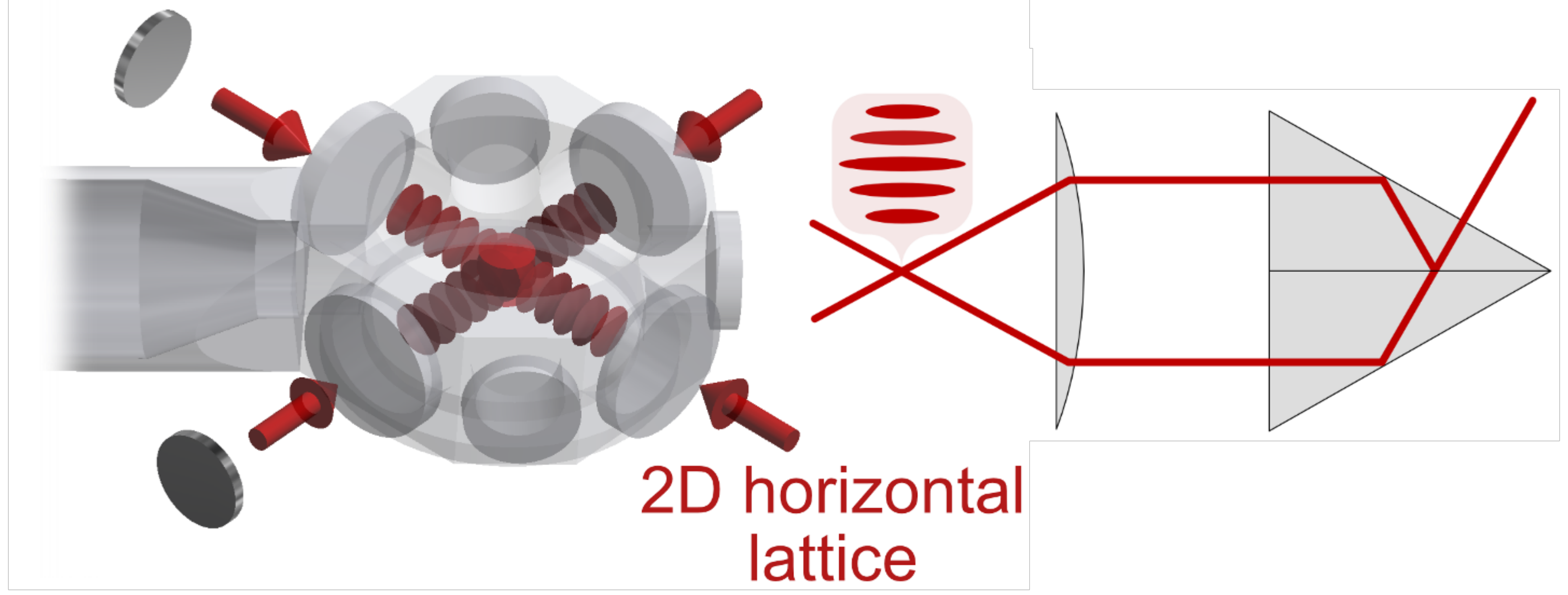

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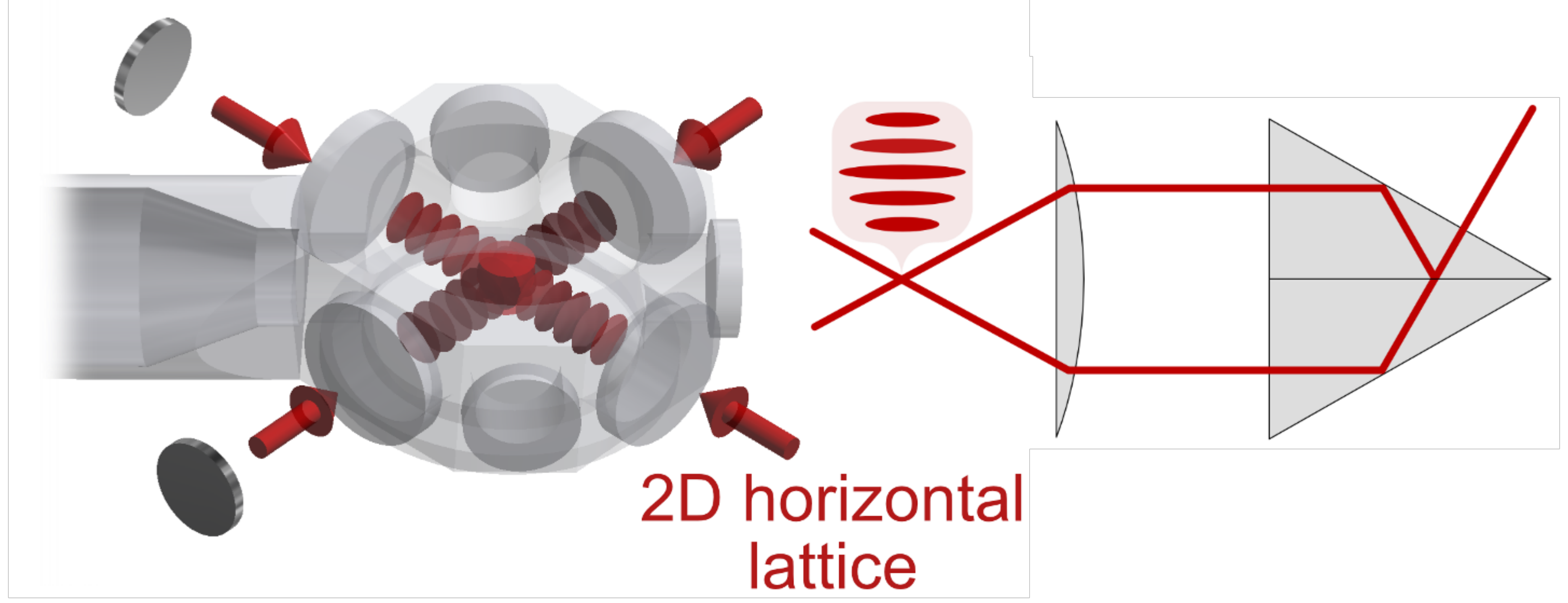
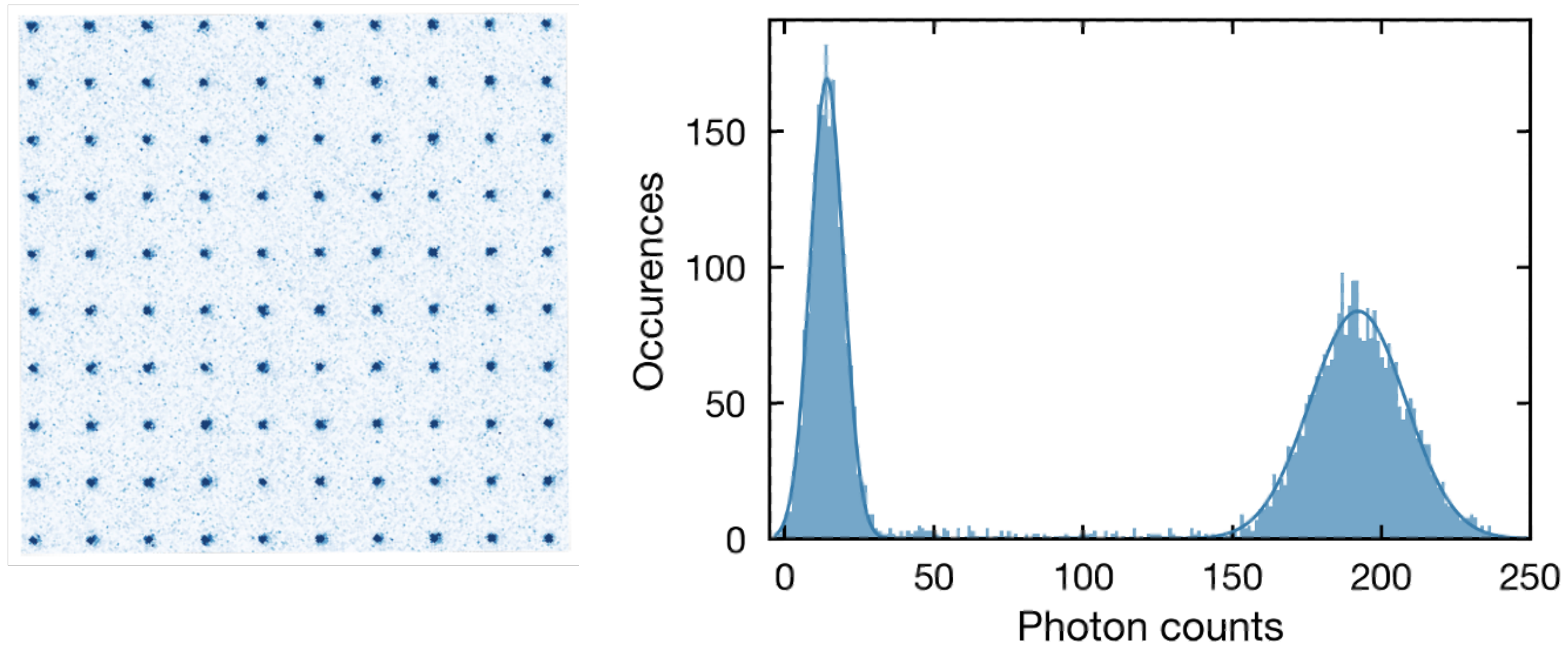
→ 3D ground-state cooling in lattice

Current status of the experimental setup

3D magic-wavelength lattice + 2D tweezer arrays(s)





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+

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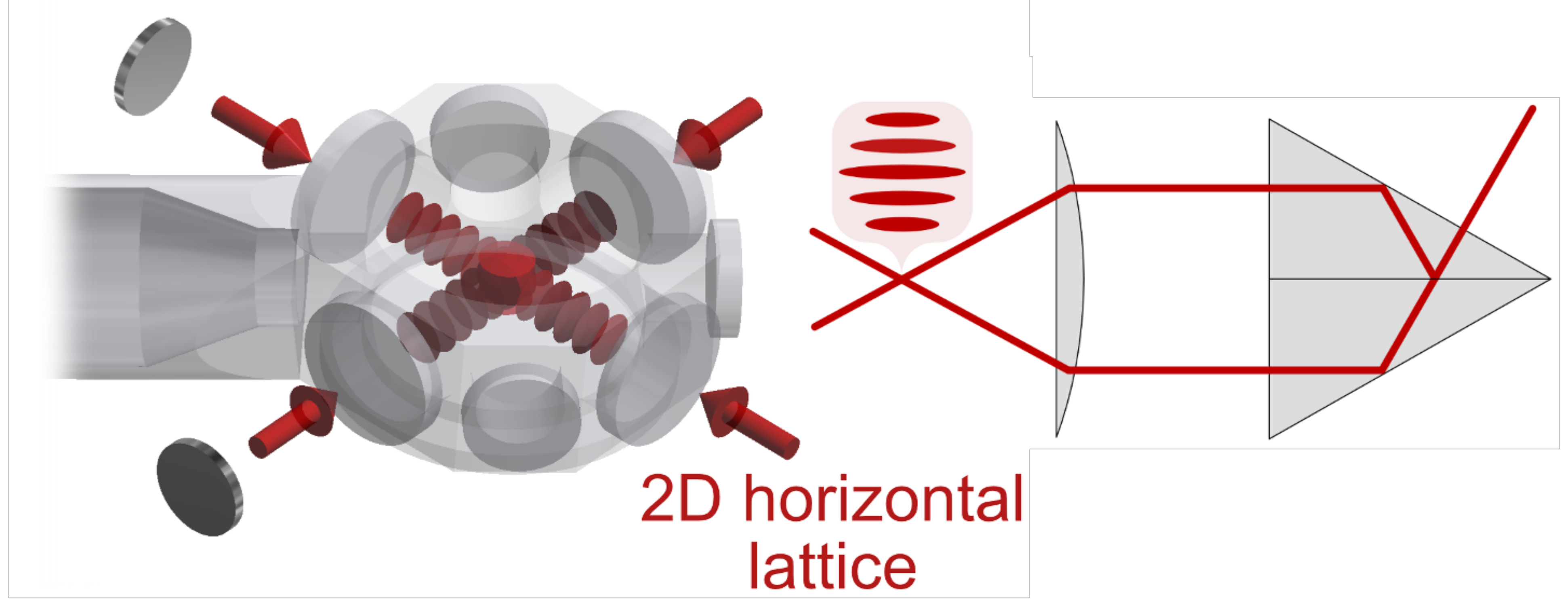

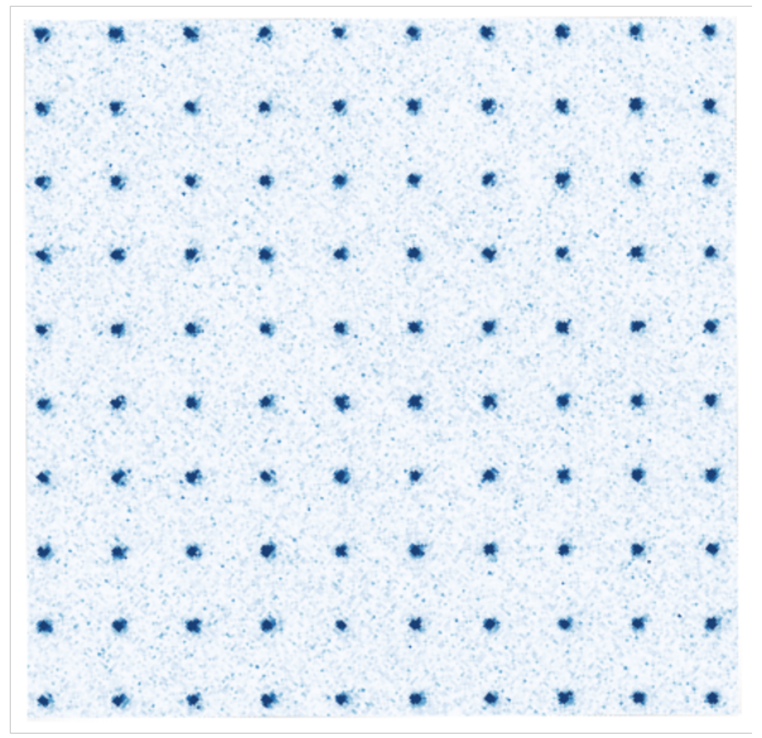

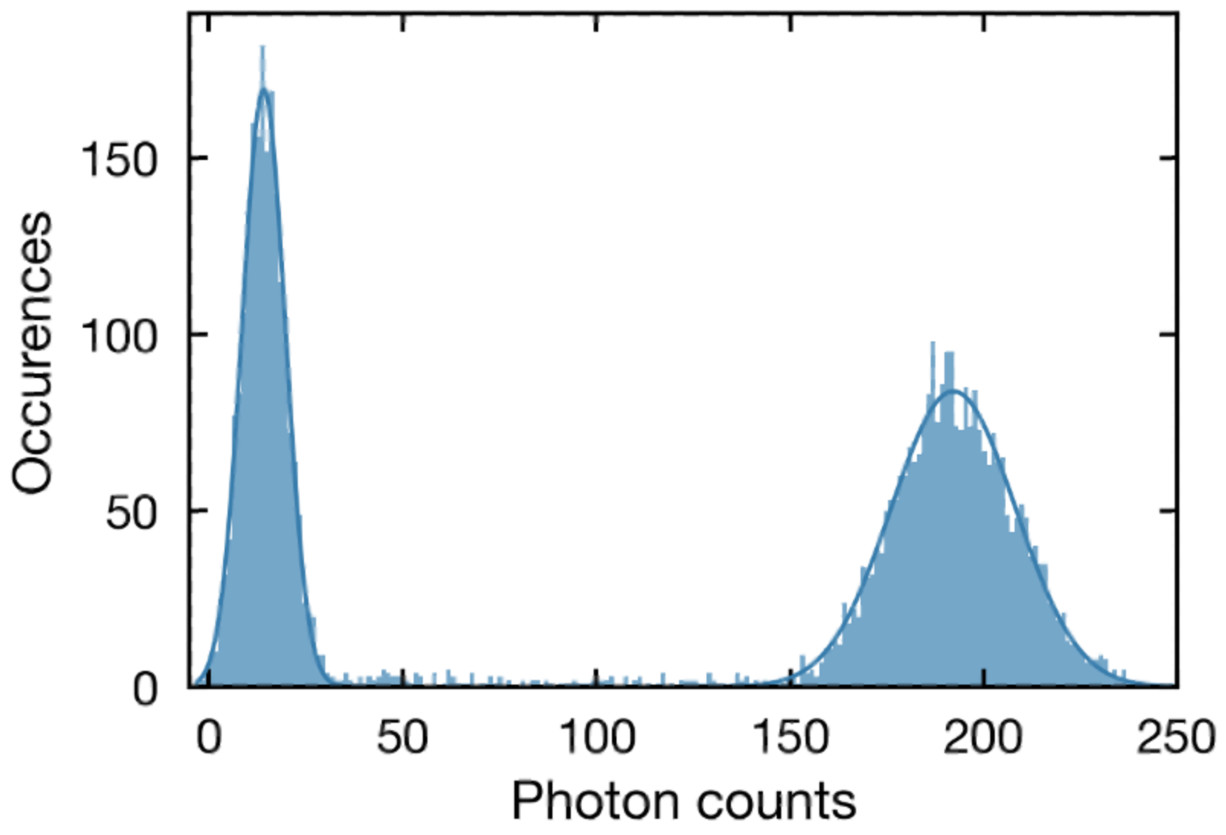

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- 532nm tweezer array
- Fluorescence imaging (tweezer/lattice)

Current status of the experimental setup

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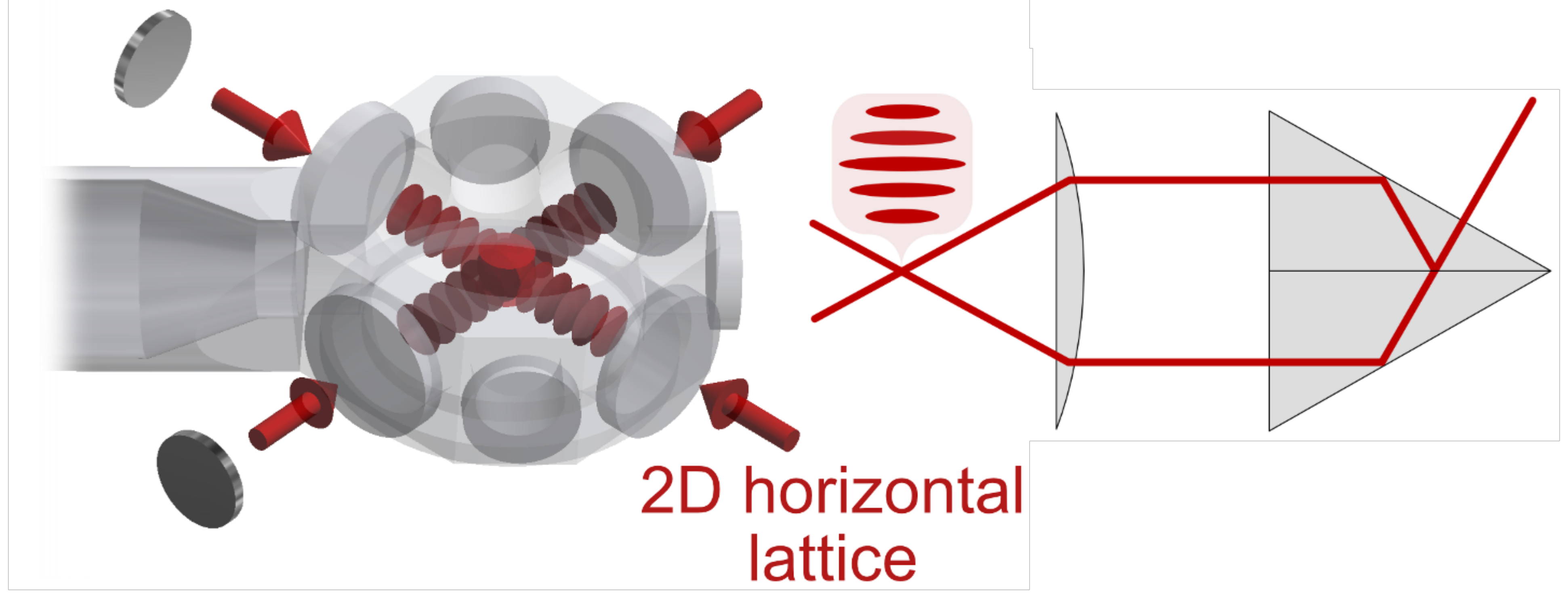

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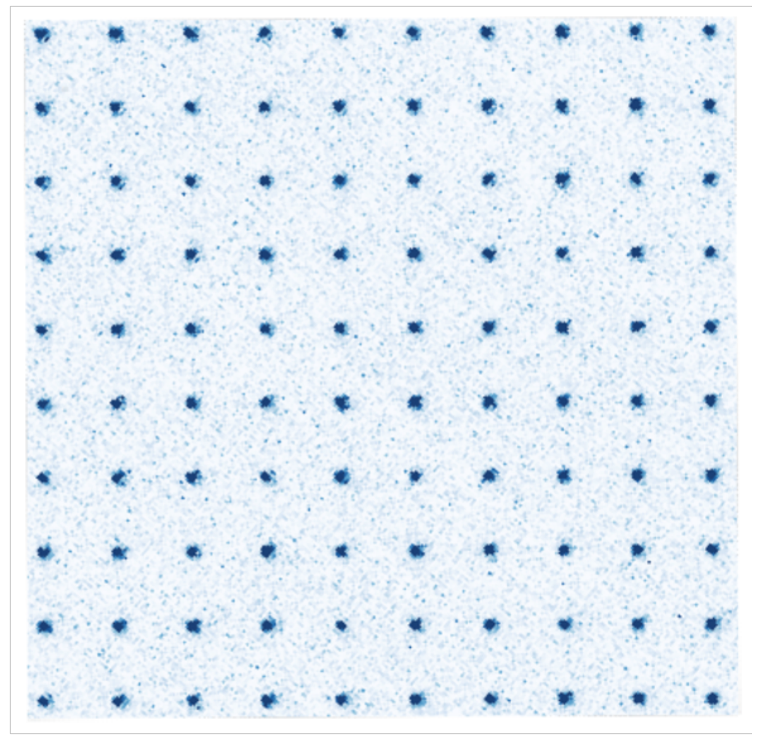
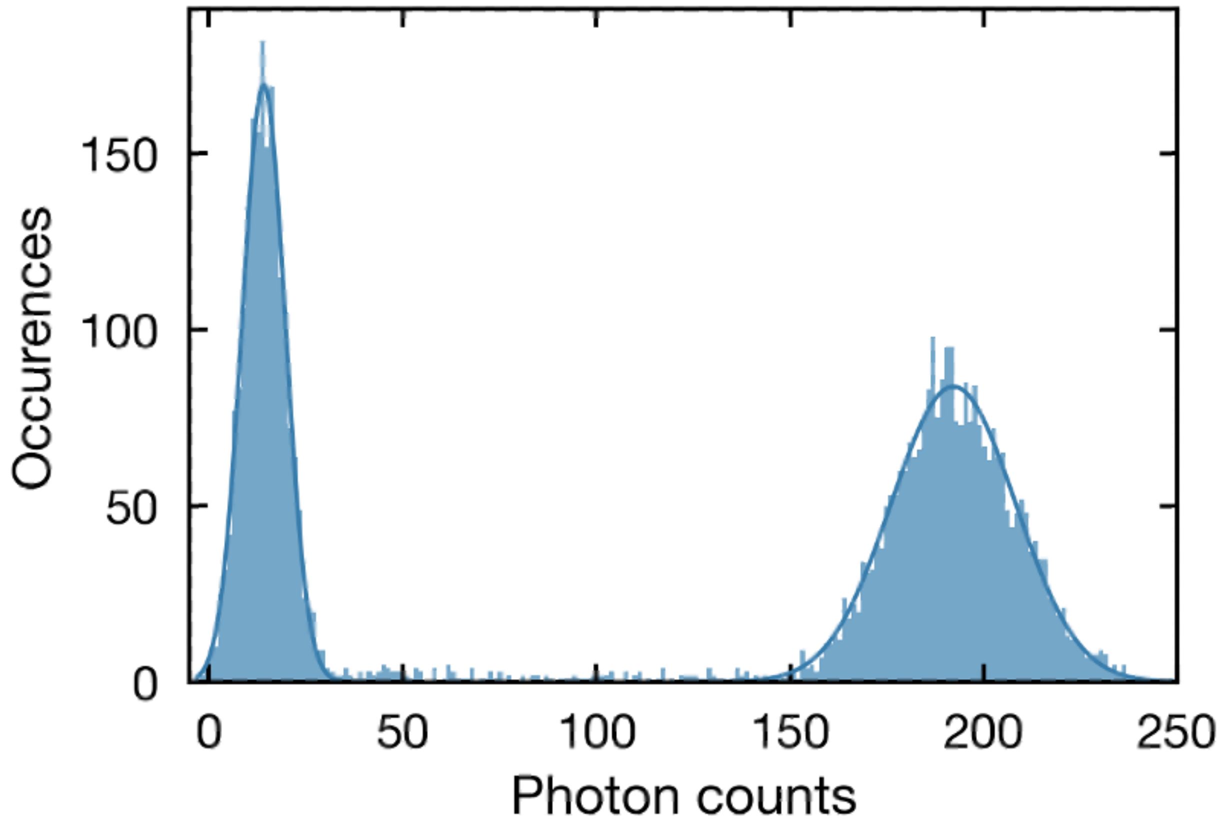
2D tweezer arrays(s)





- 532nm tweezer array
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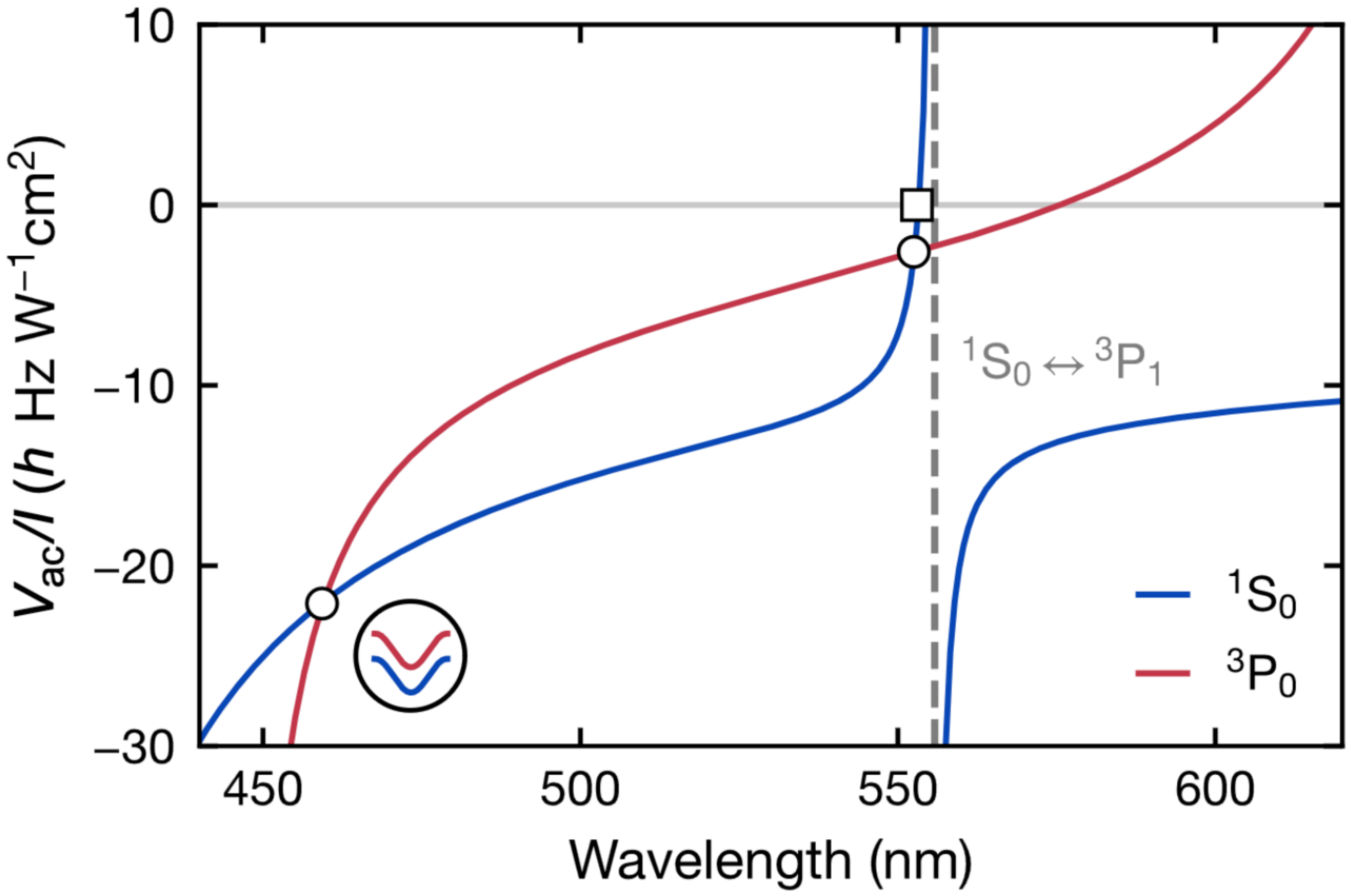
→ State-dependent control

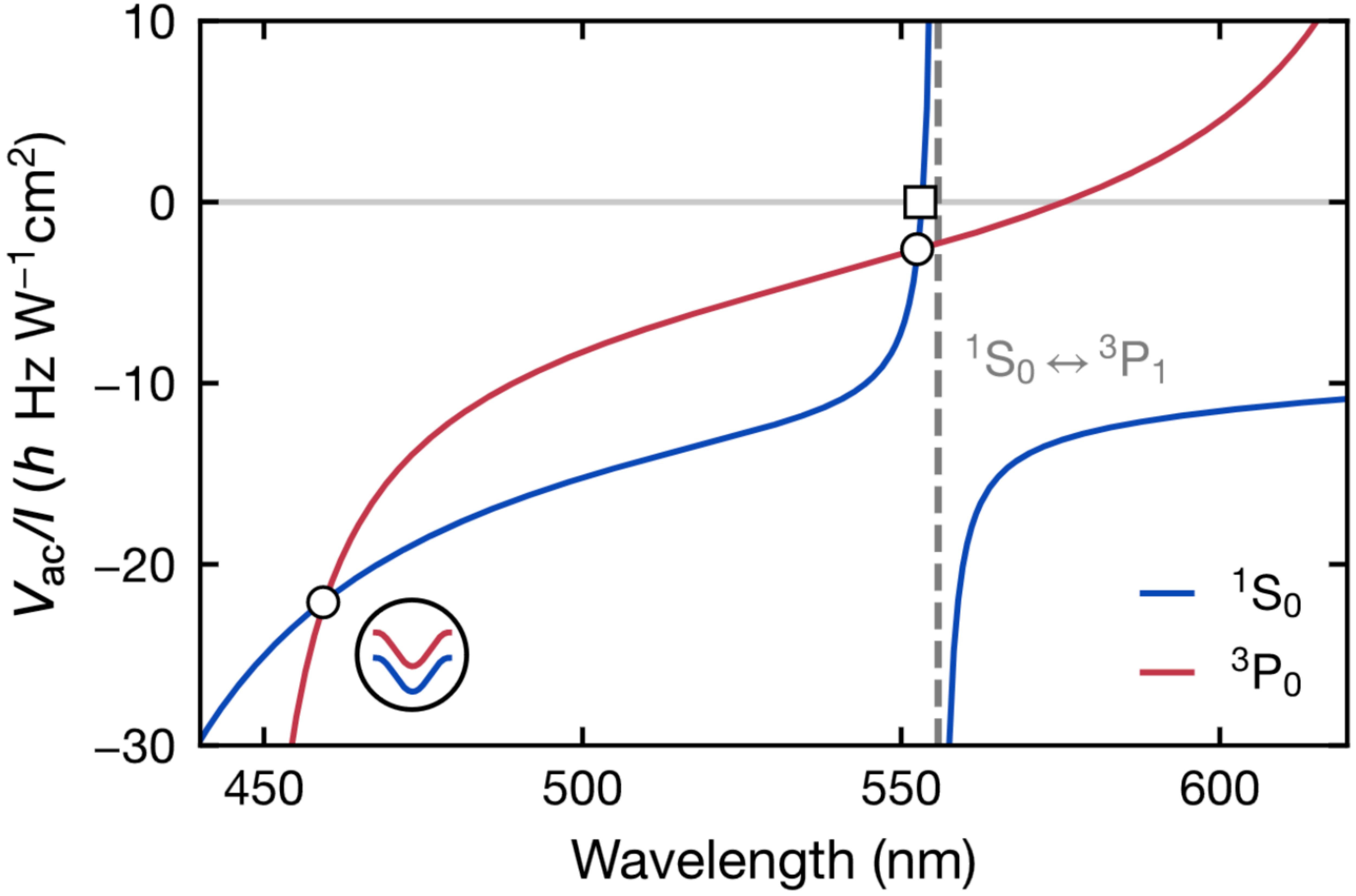
→ Tune-out tweezer array

State-dependent control



Höhn, Staub, Brochier, Darkwah Oppong, Aidelsburger, Phys. Rev. A **108**, 053325 (2023)

State-dependent control



Magic wavelength:
differential shift vanishes

Höhn, Staub, Brochier, Darkwah Oppong, Aidelsburger, Phys. Rev. A **108**, 053325 (2023)

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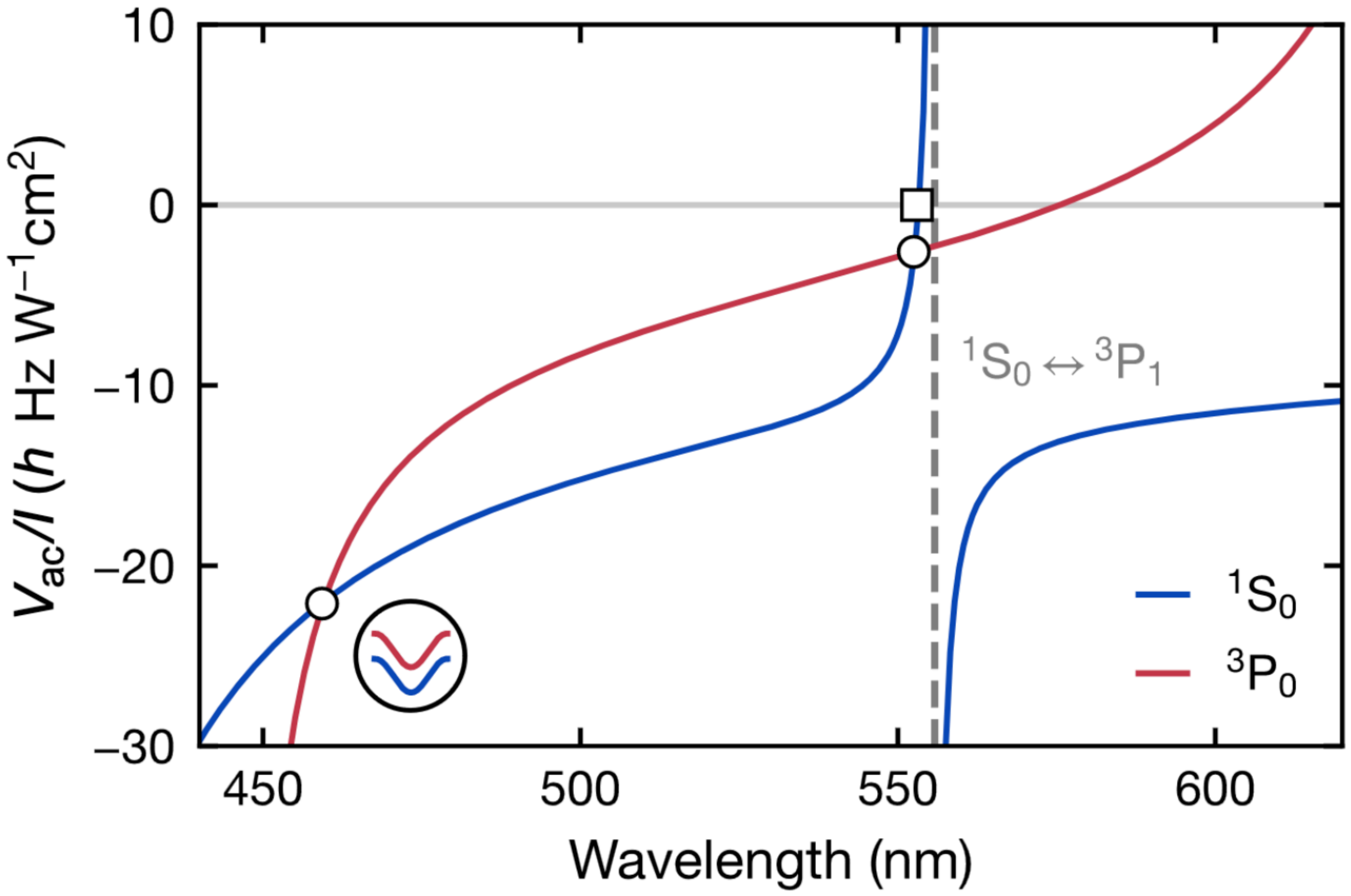

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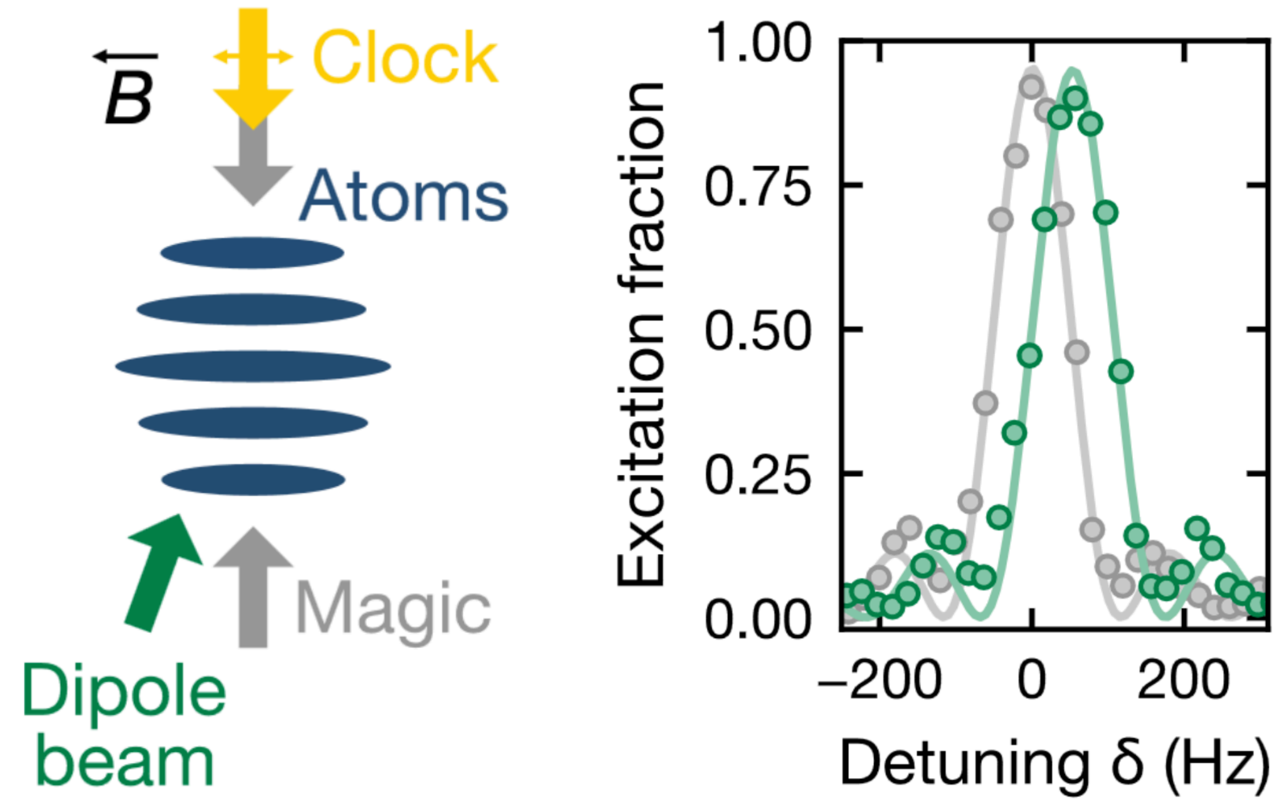

Höhn, Staub, Brochier, Darkwah Oppong, Aidelsburger, Phys. Rev. A **108**, 053325 (2023)

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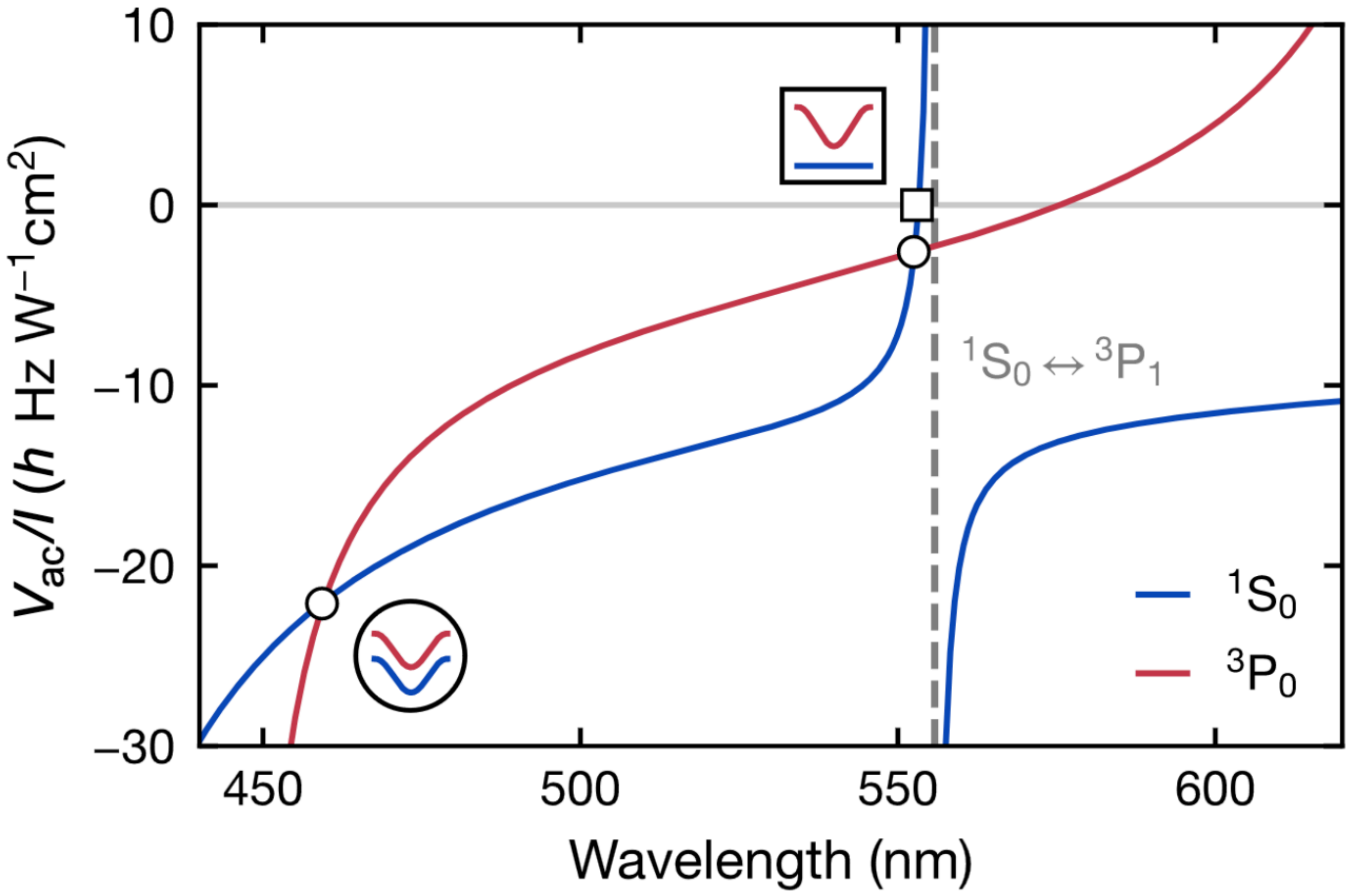

Tune-out wavelength:
zero-crossing of AC pol.

Höhn, Staub, Brochier, Darkwah Oppong, Aidelsburger, Phys. Rev. A **108**, 053325 (2023)

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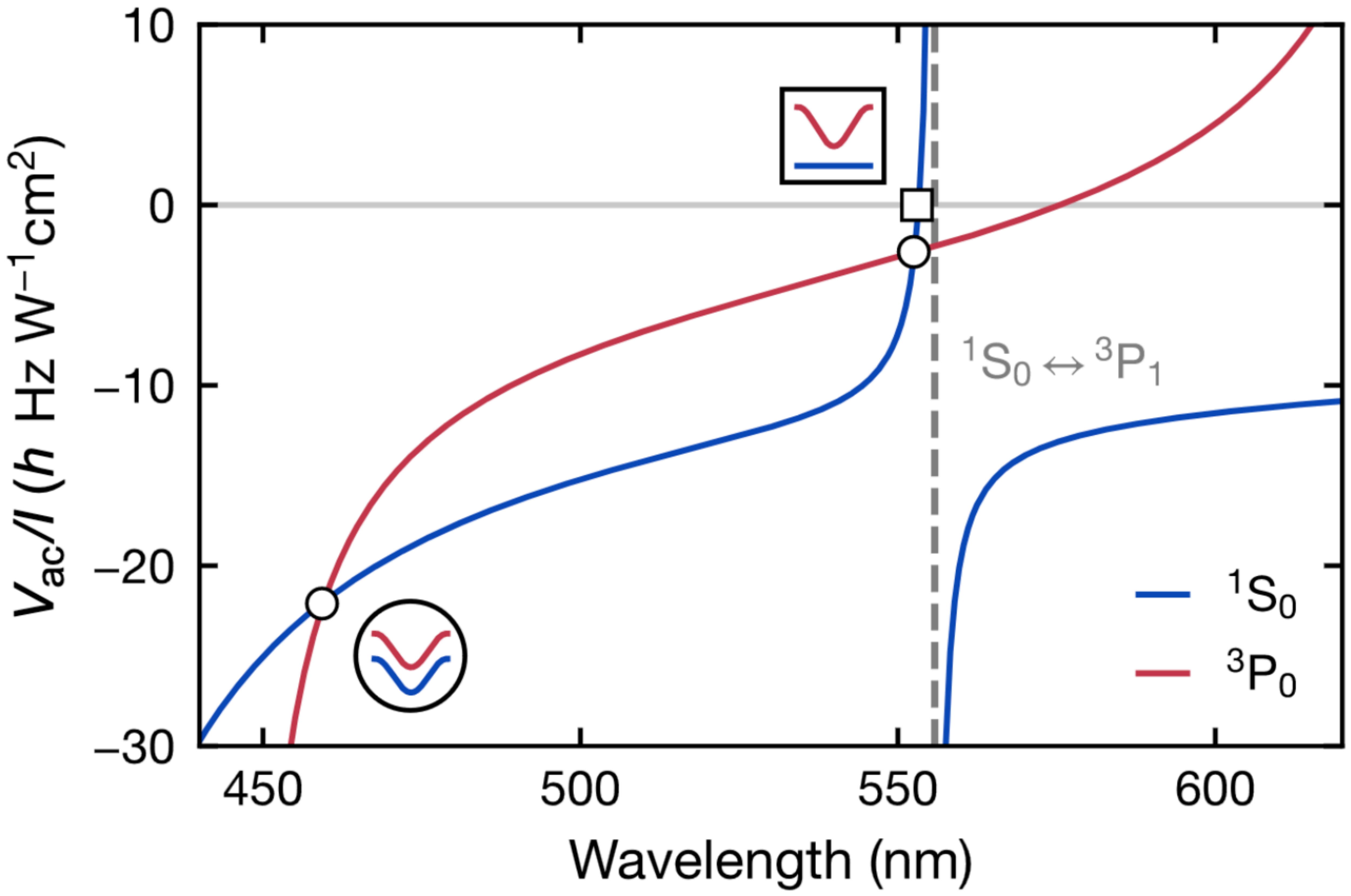

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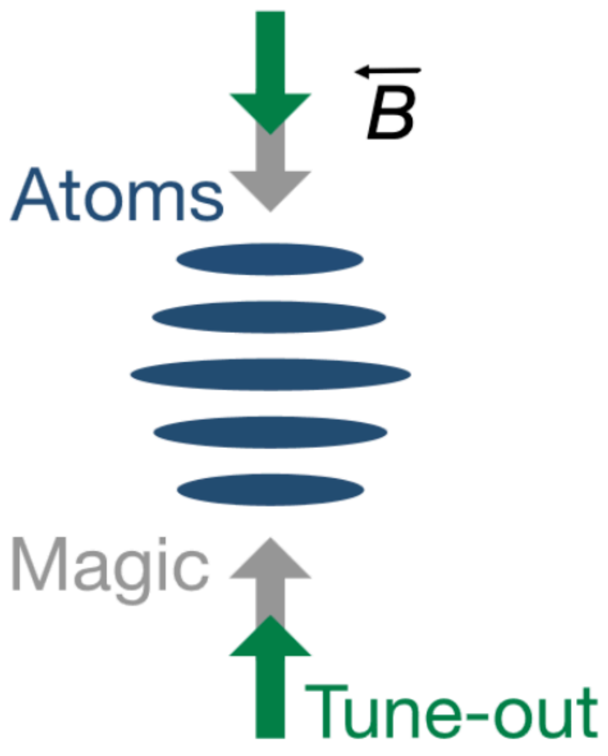

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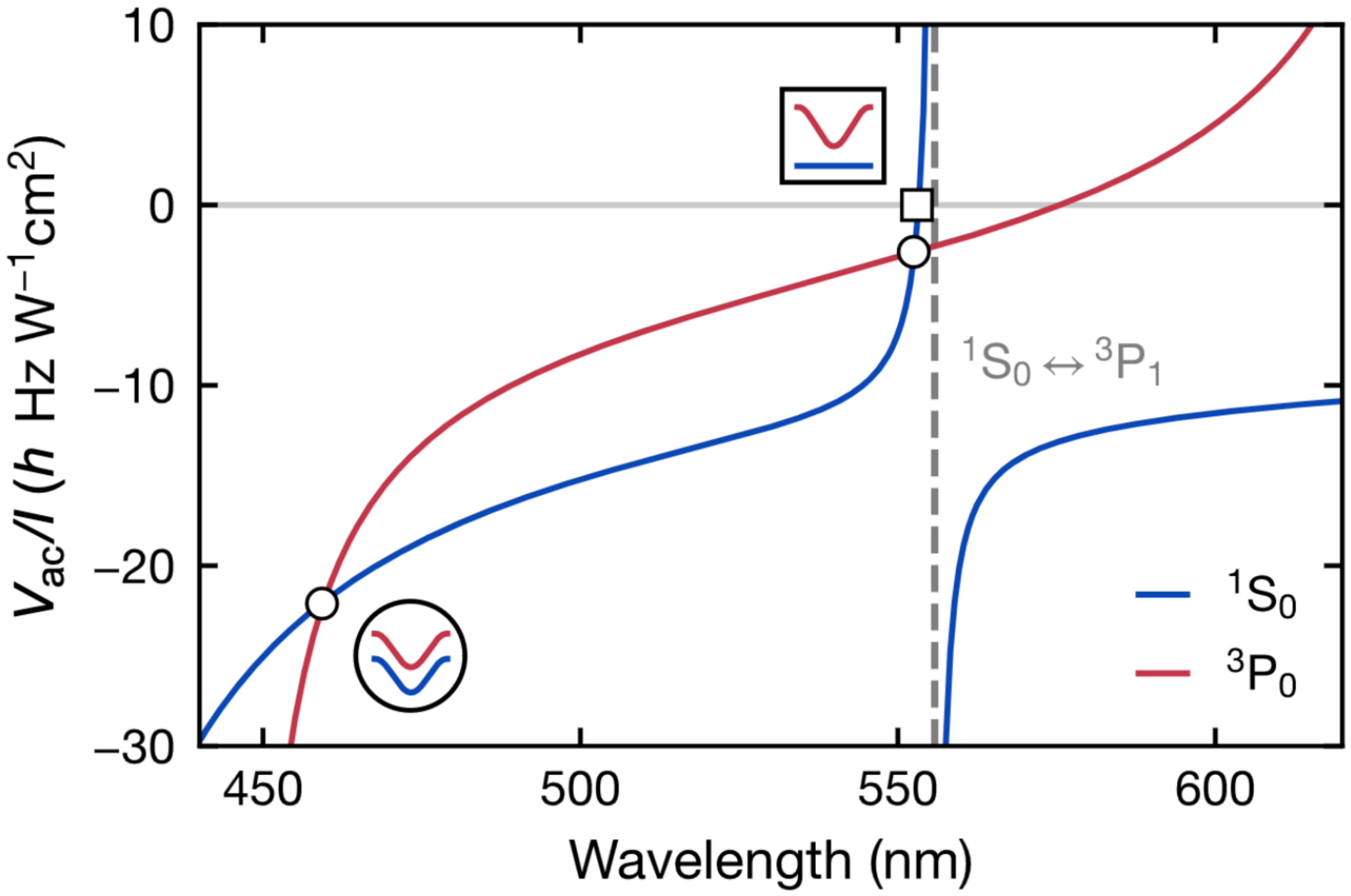

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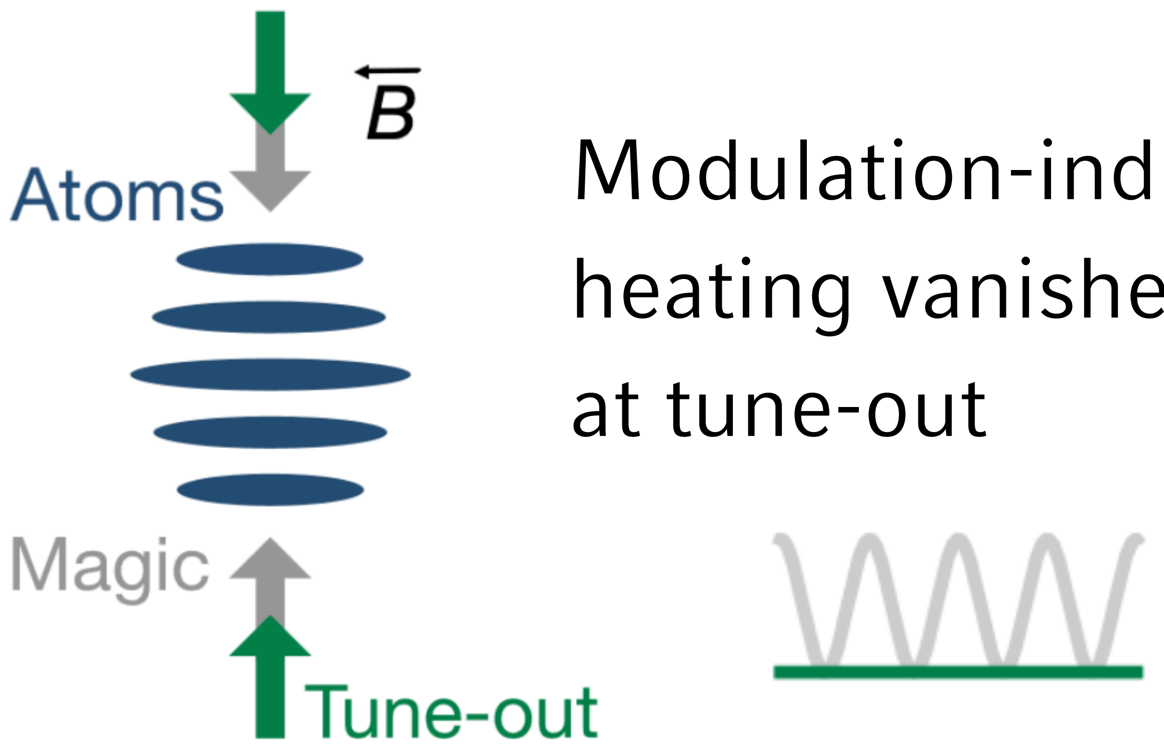
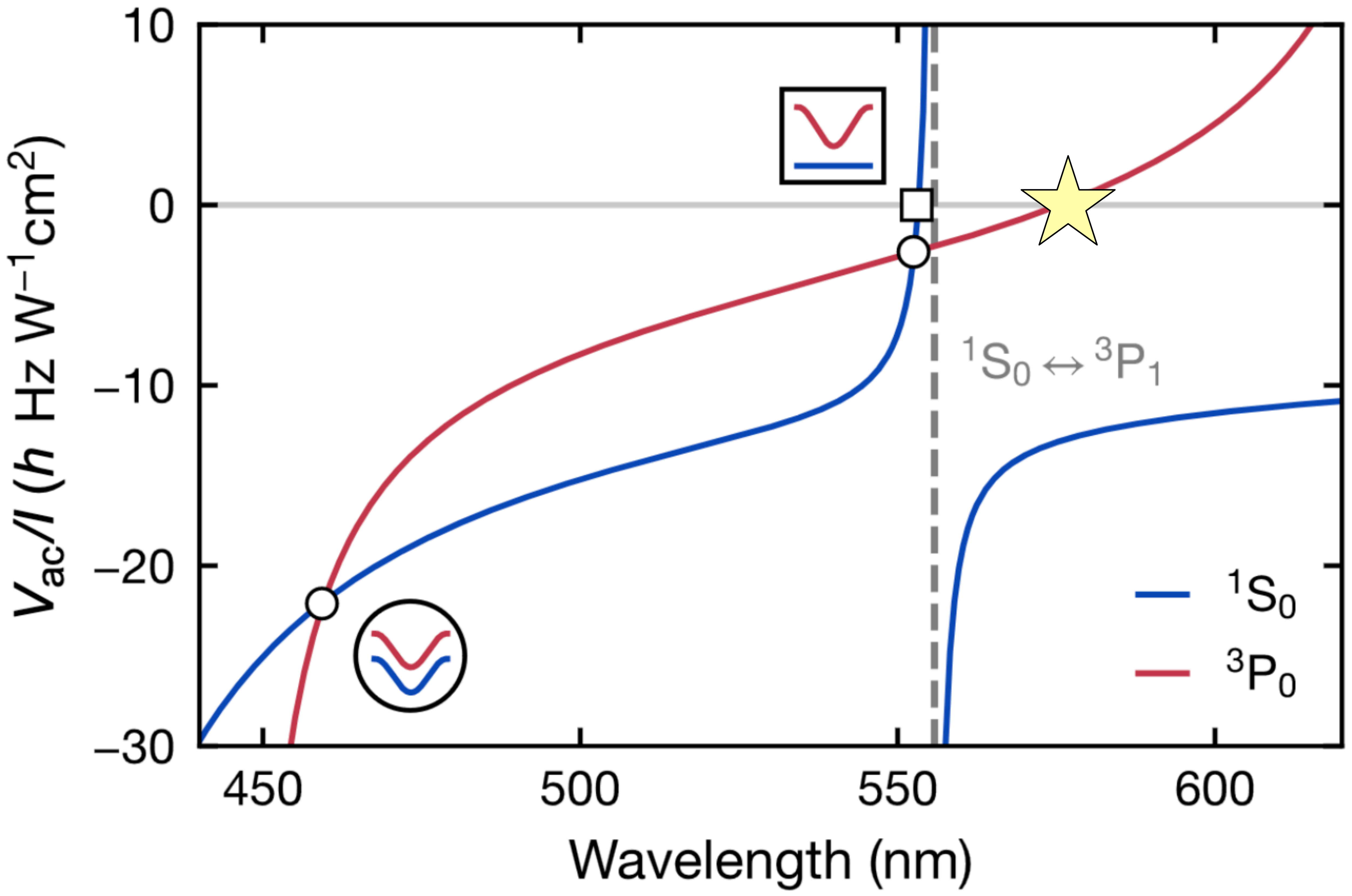


Modulation-induced heating vanishes at tune-out

Höhn, Staub, Brochier, Darkwah Oppong, Aidelsburger, Phys. Rev. A **108**, 053325 (2023)

State-dependent control



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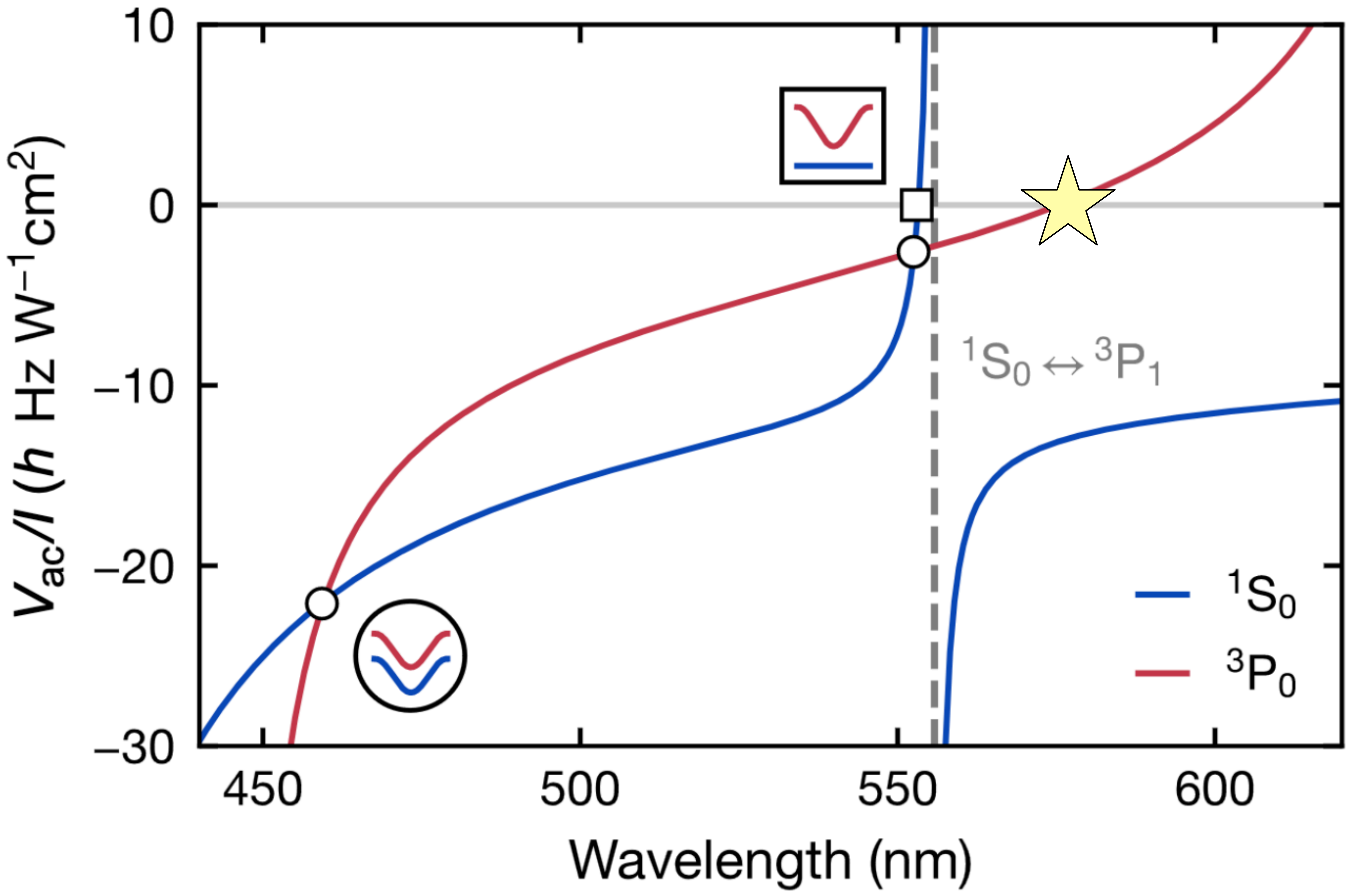
Höhn, Staub, Brochier, Darkwah Oppong, Aidelsburger, Phys. Rev. A **108**, 053325 (2023)

State-dependent control



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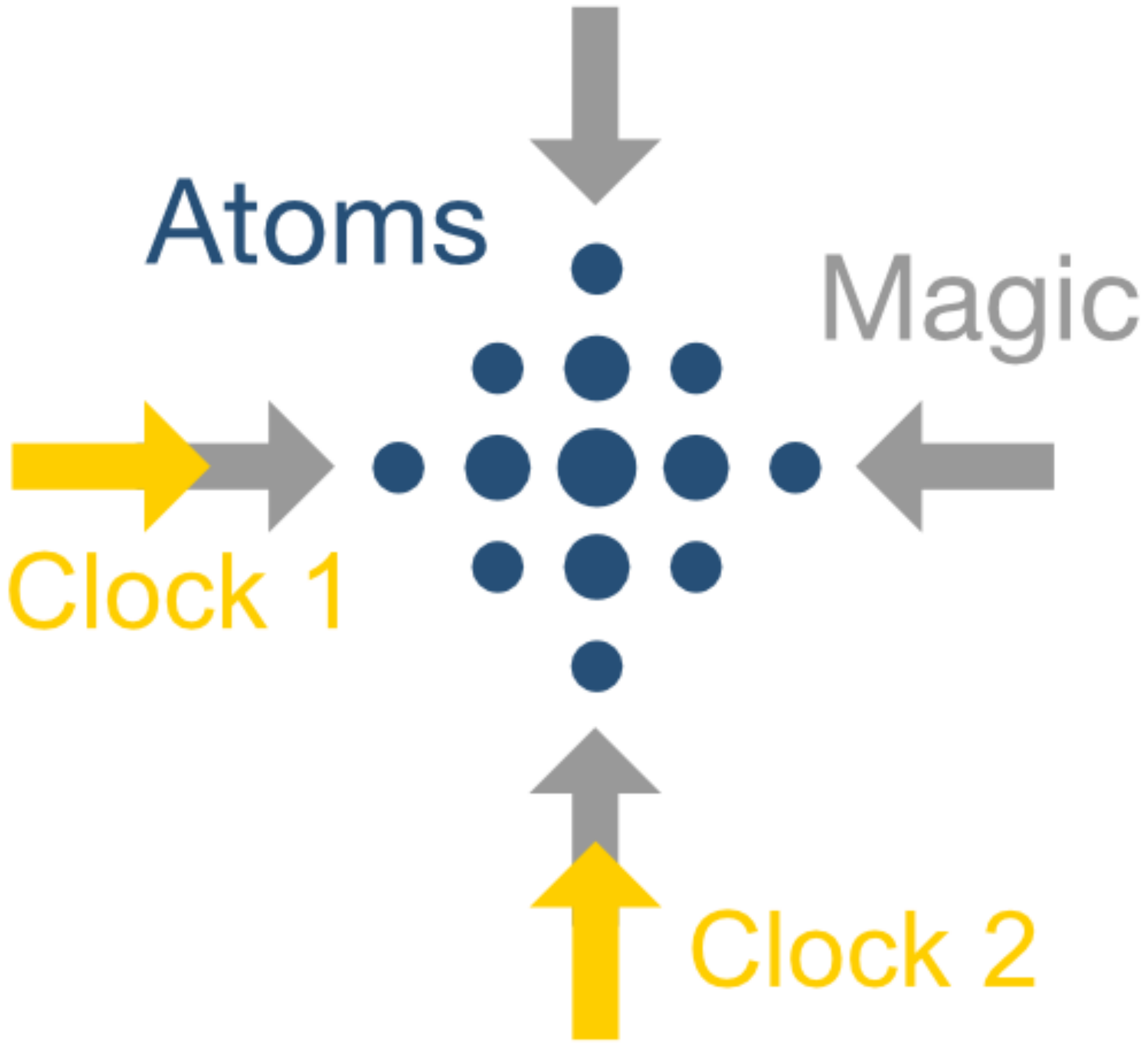
e-tune-out results in preparation!

Höhn, Staub, Brochier, Darkwah Oppong, Aidelsburger, Phys. Rev. A **108**, 053325 (2023)

Direct laser cooling on the ultra-narrow optical clock

2D clock cooling

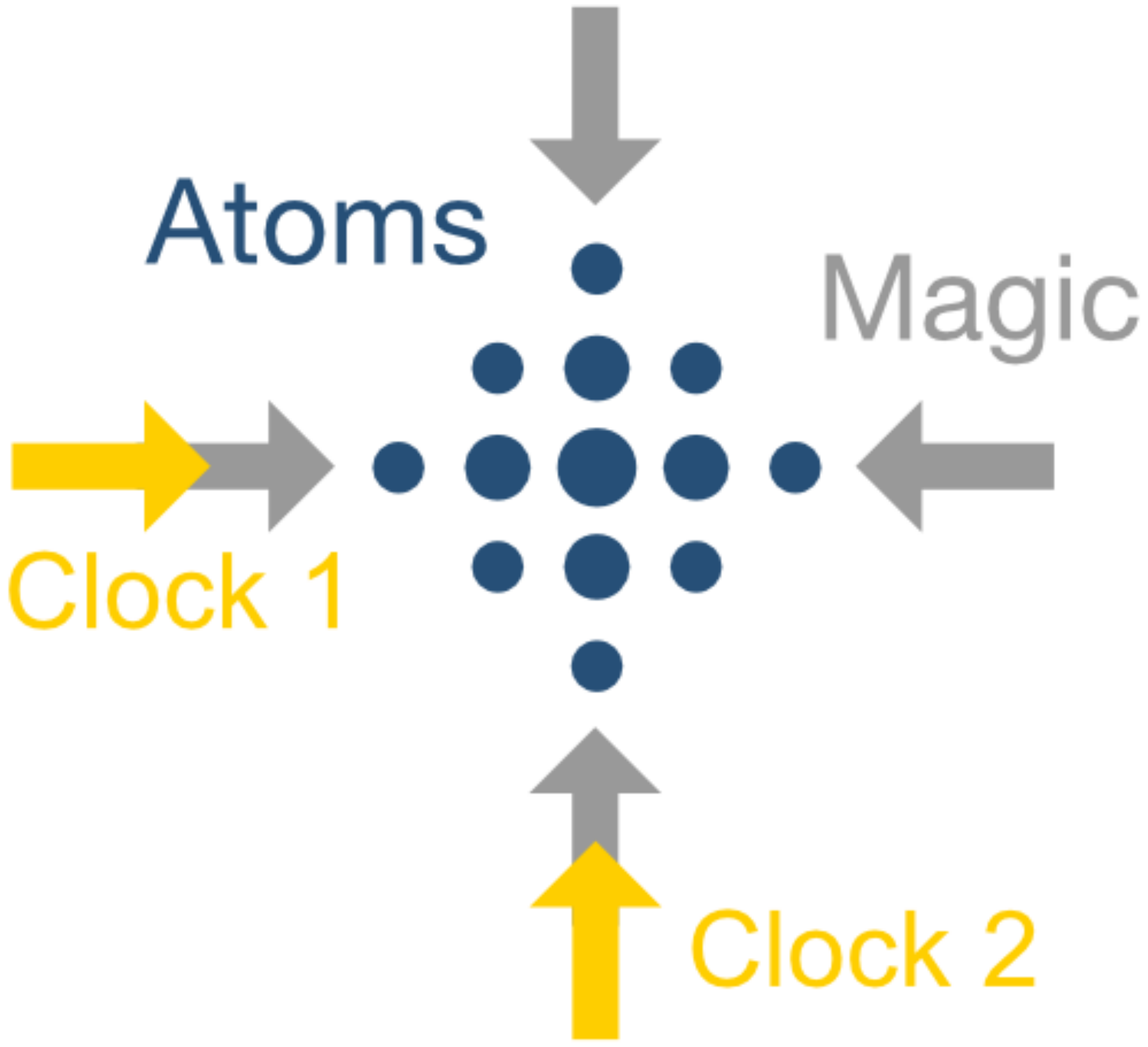


Experimental setup:

- Two independent clock beams along horizontal lattice axis
- One repumping beam to $^3D_1$ co-propagating with clock 1

E. Curtis *et al.*, Phys. Rev. A **64**, 031043 (2001); N. Nemitz *et al.*, Nat. Phot. **10**, 258 (2016)

2D clock cooling



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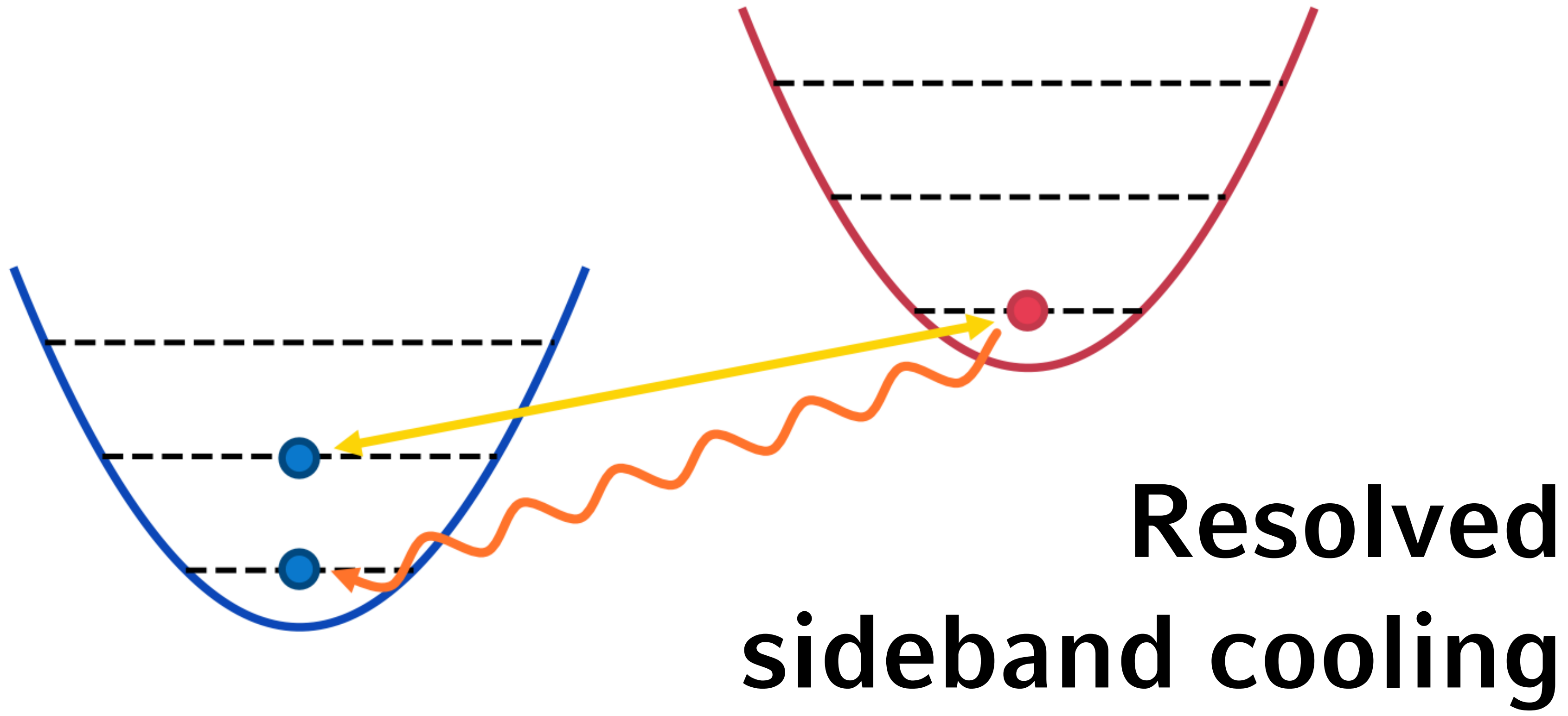

E. Curtis *et al.*, Phys. Rev. A **64**, 031043 (2001); N. Nemitz *et al.*, Nat. Phot. **10**, 258 (2016)

2D clock cooling

Direct loading after compressed MOT:

2D clock cooling

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- Simulate lineshape for 2D lattice
- Inhomogeneity crucial
- Typically longer-tail distributions: effect of 2^{nd} sideband is more prominent

2D clock cooling

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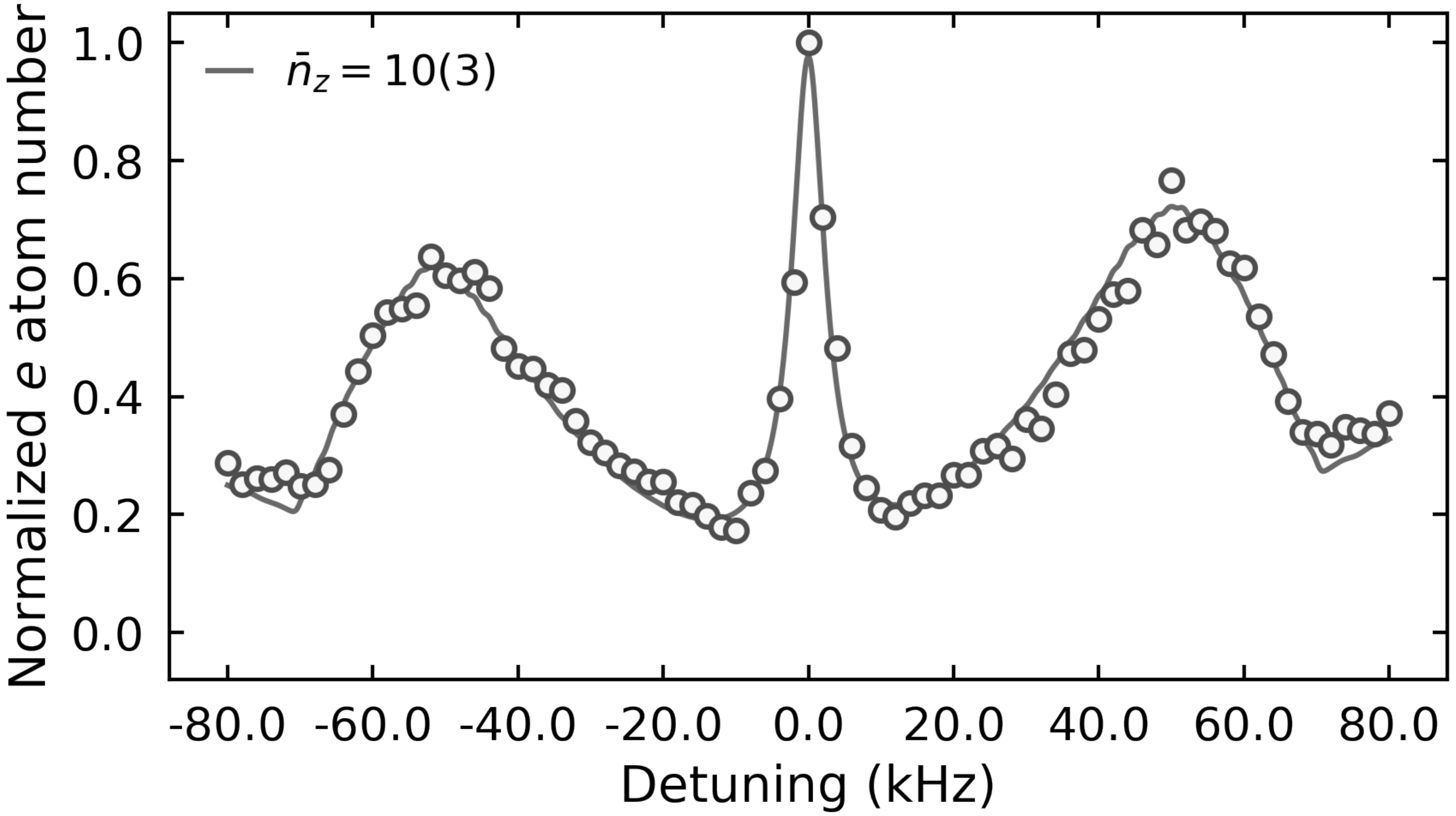

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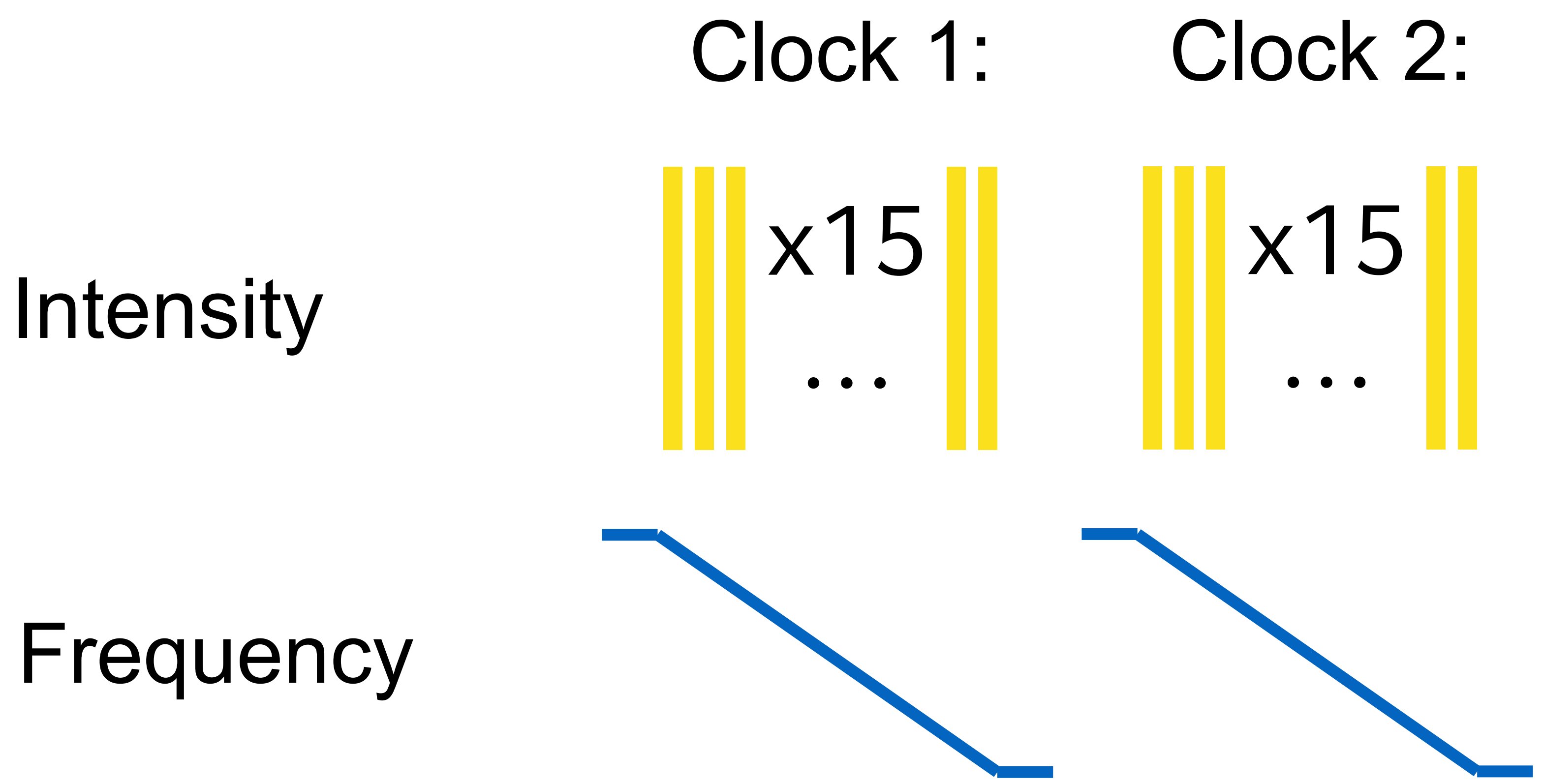
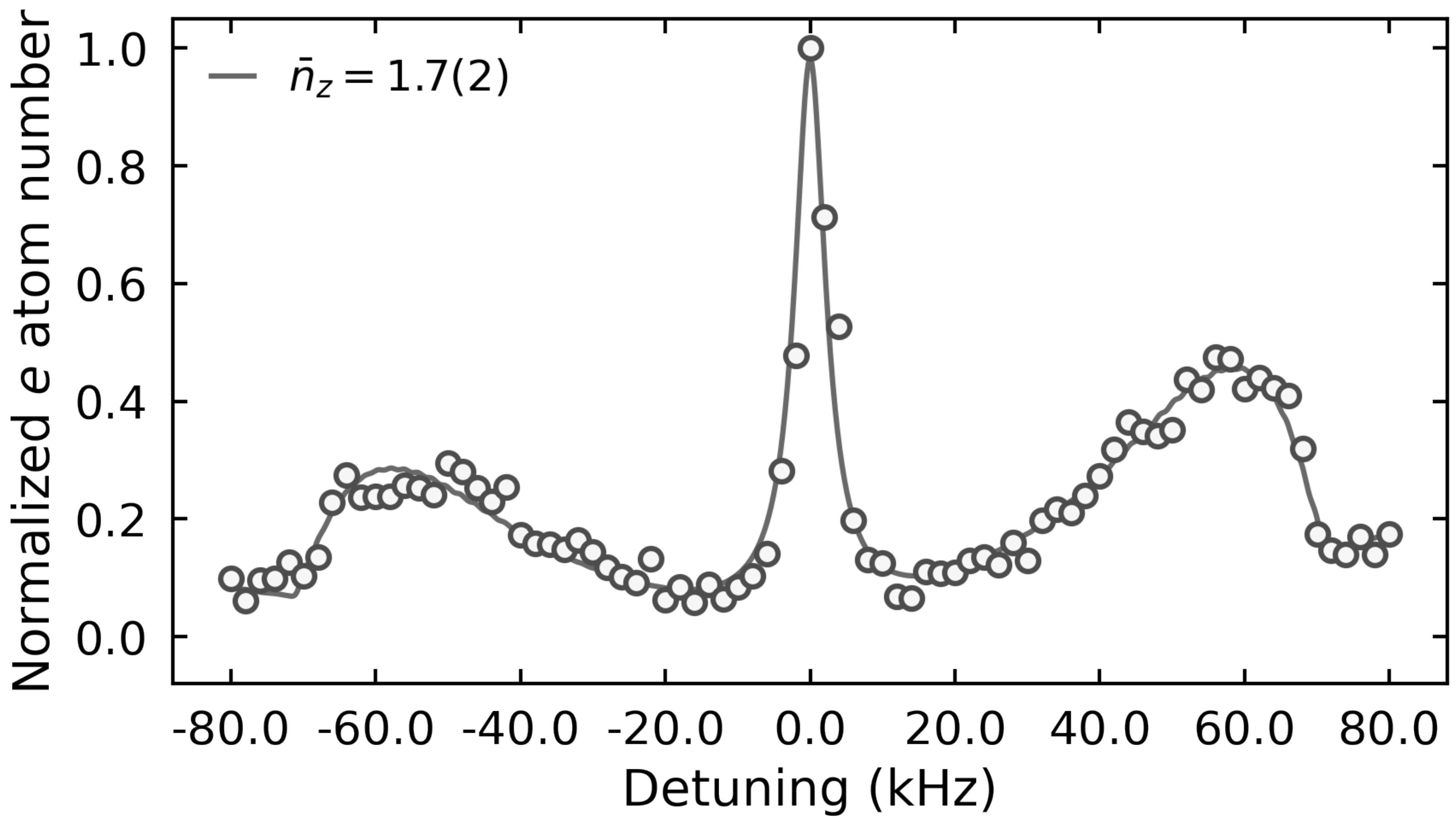
2D clock cooling

Cooling with frequency sweep:





2D clock cooling

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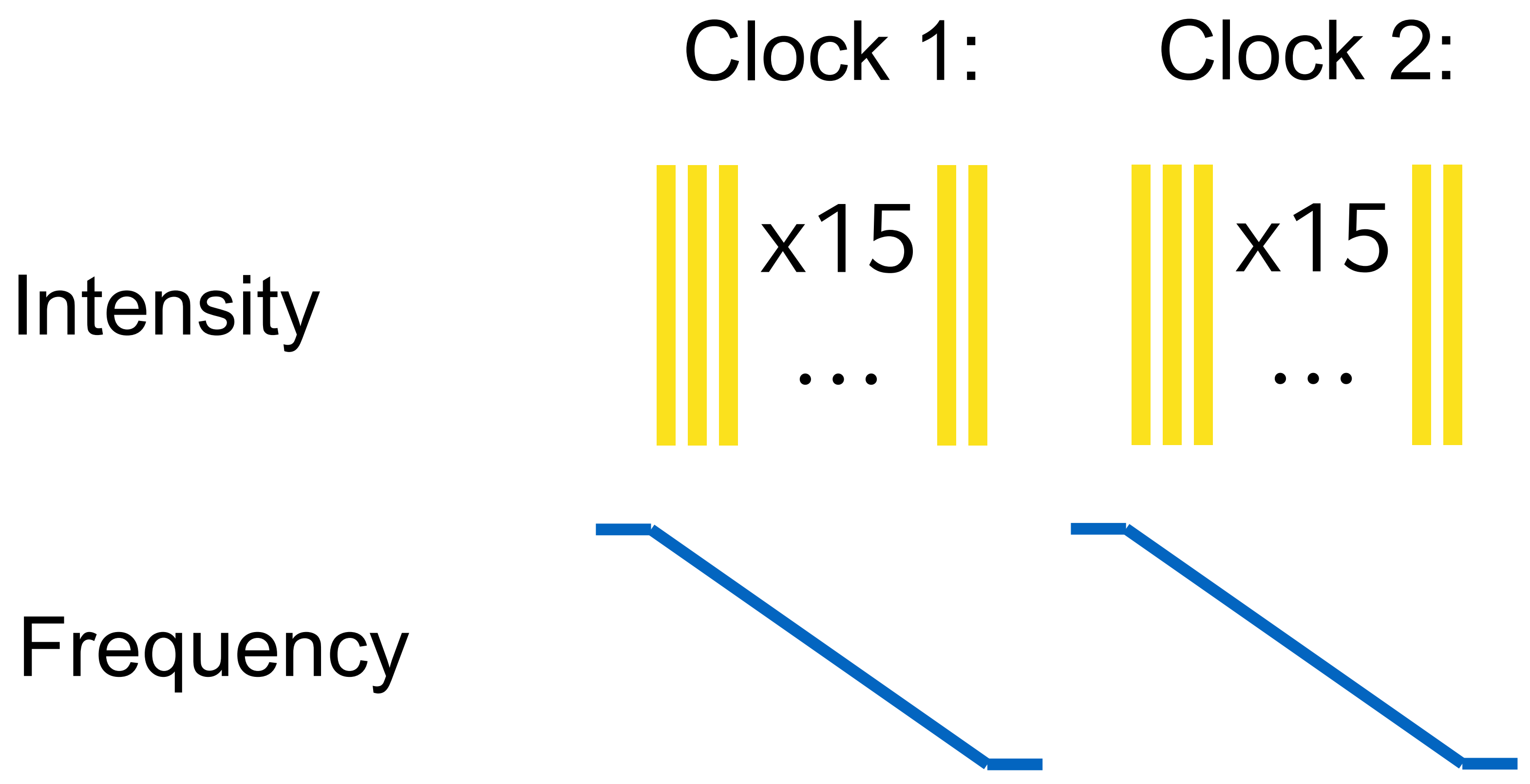

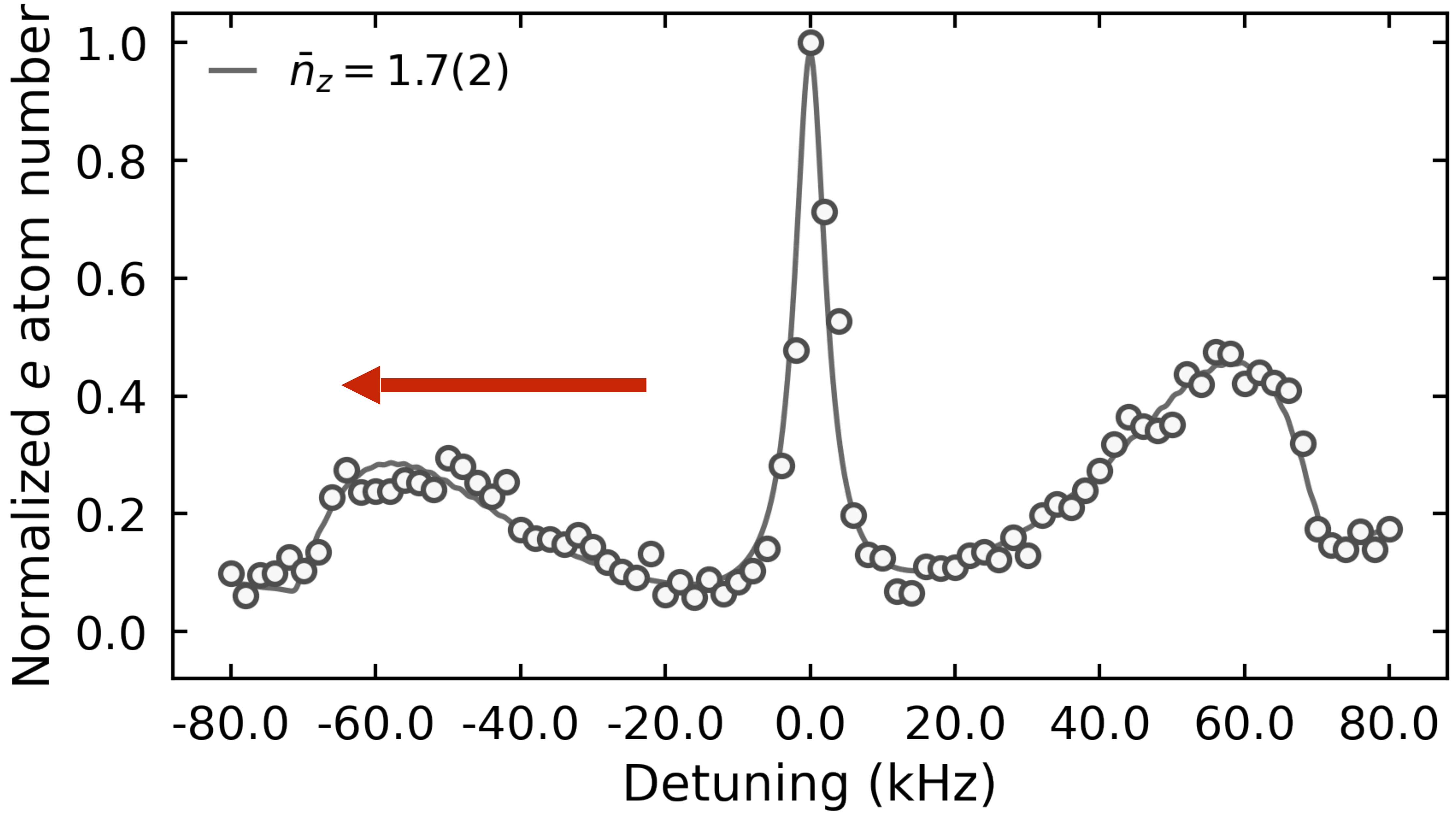

→ Sweeping the sideband detuning

2D clock cooling

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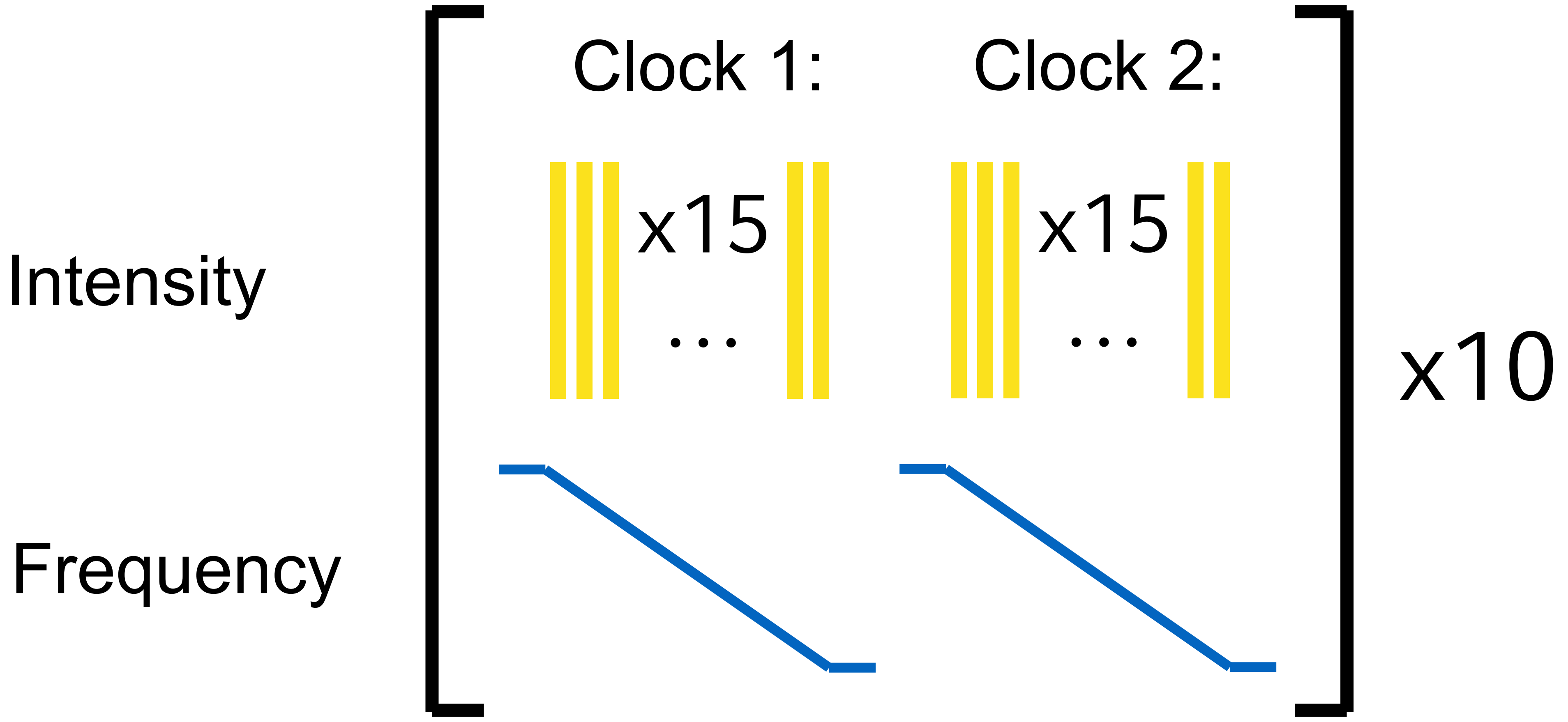
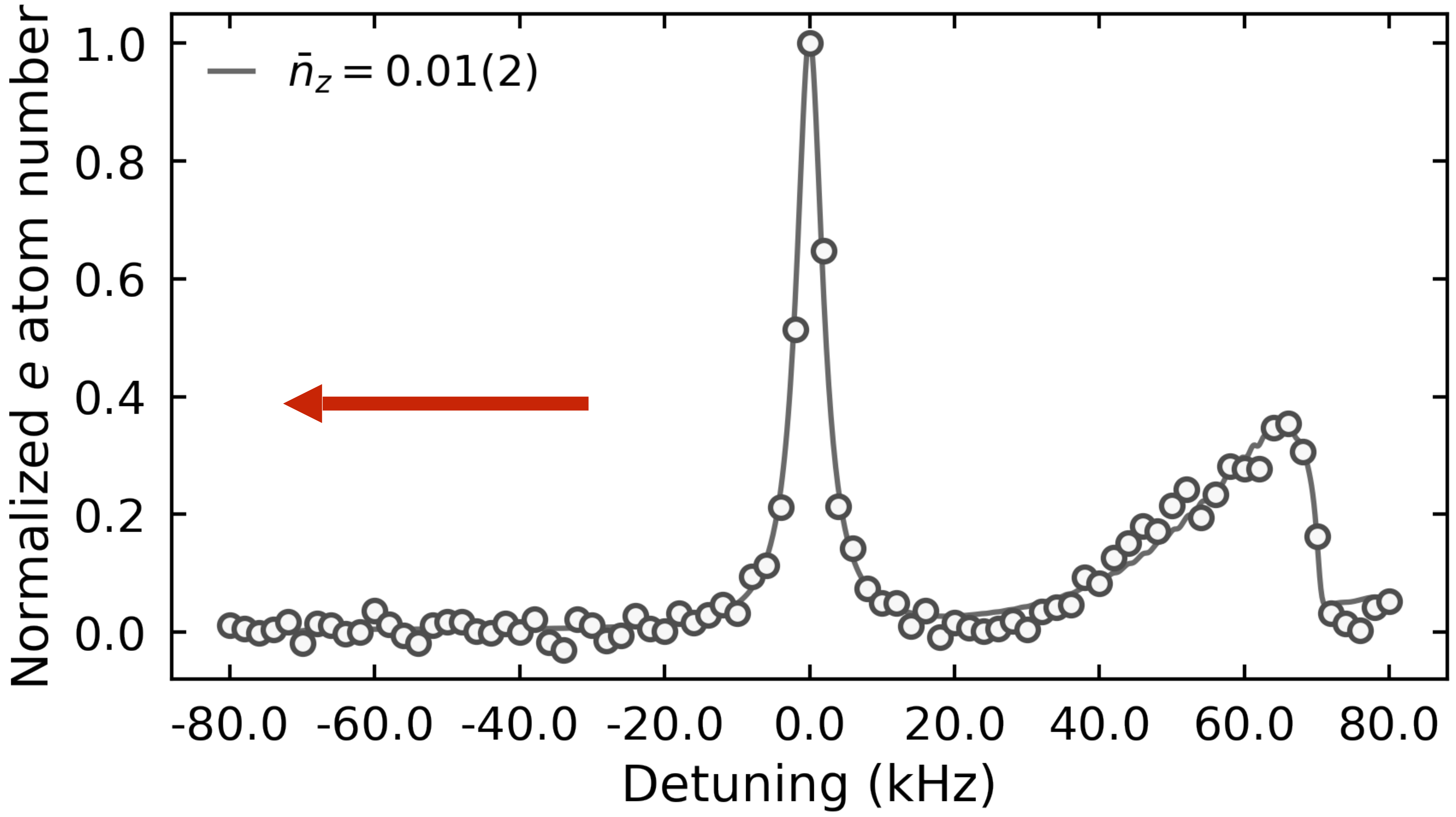
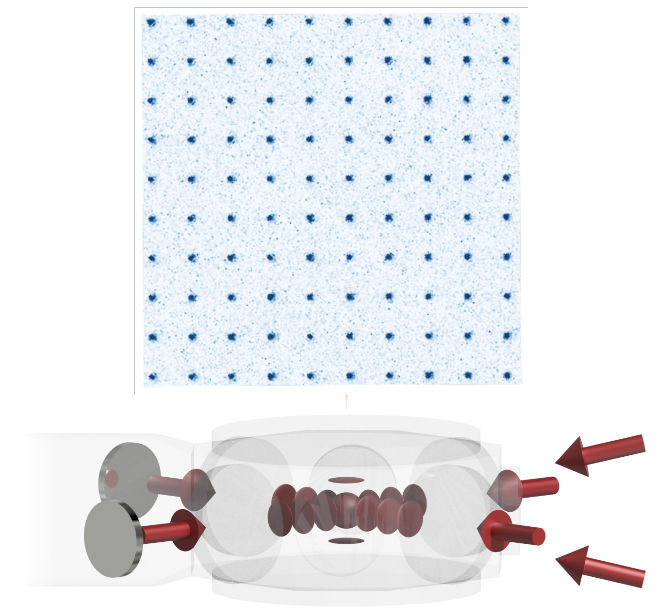


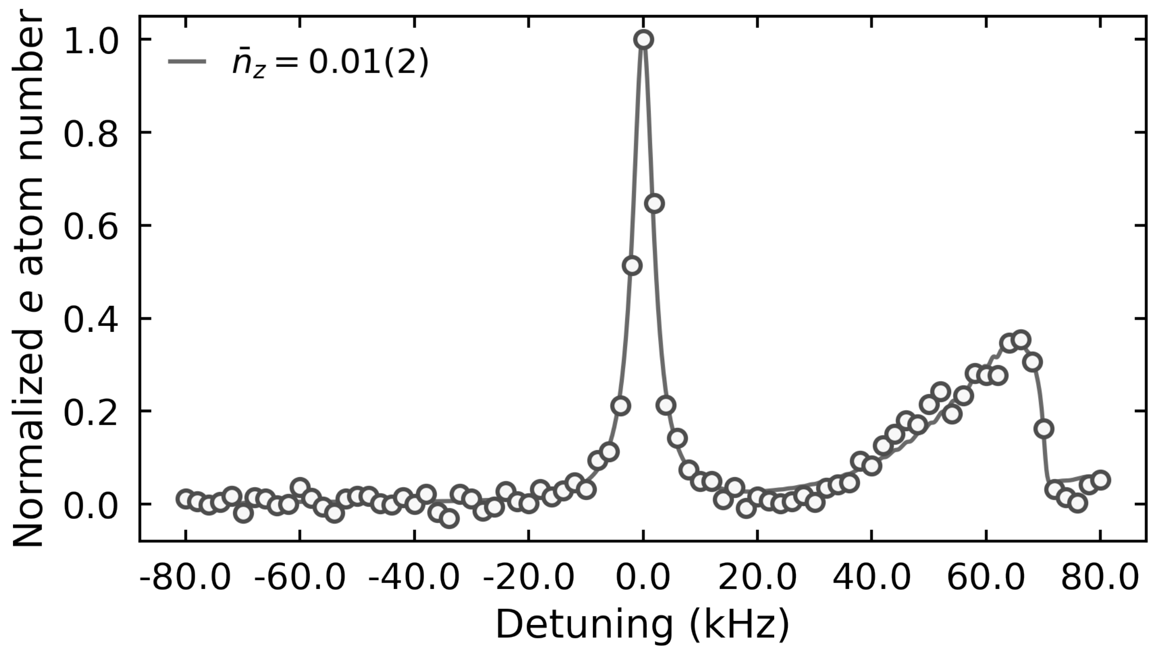


→ Sweeping the sideband detuning

Summary & Outlook

Novel fermionic hybrid tweezer-lattice experiment





- 3D magic optical lattice

Höhn, Staub, Brochier, Darkwah Oppong, Aidelsburger, Phys. Rev. A **108**, 053325 (2023)
Surace, Fromholz, Darkwah Oppong, Dalmonte, Aidelsburger, PRX Quantum **4**, 020330 (2023)

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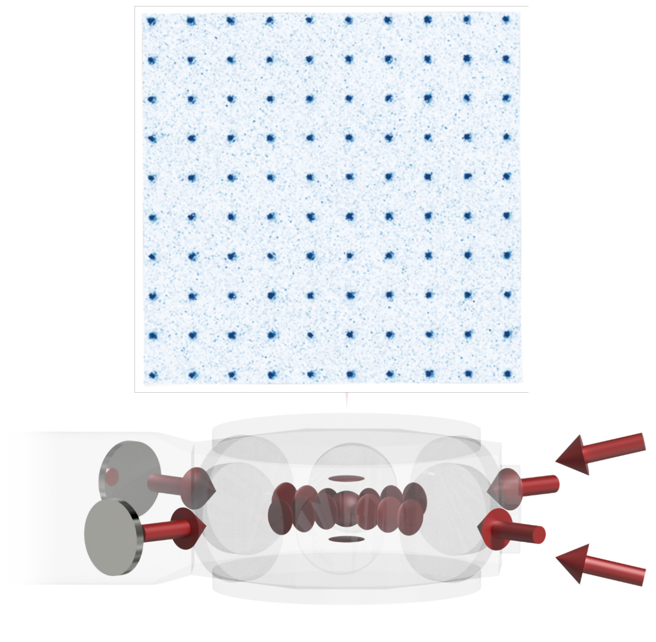

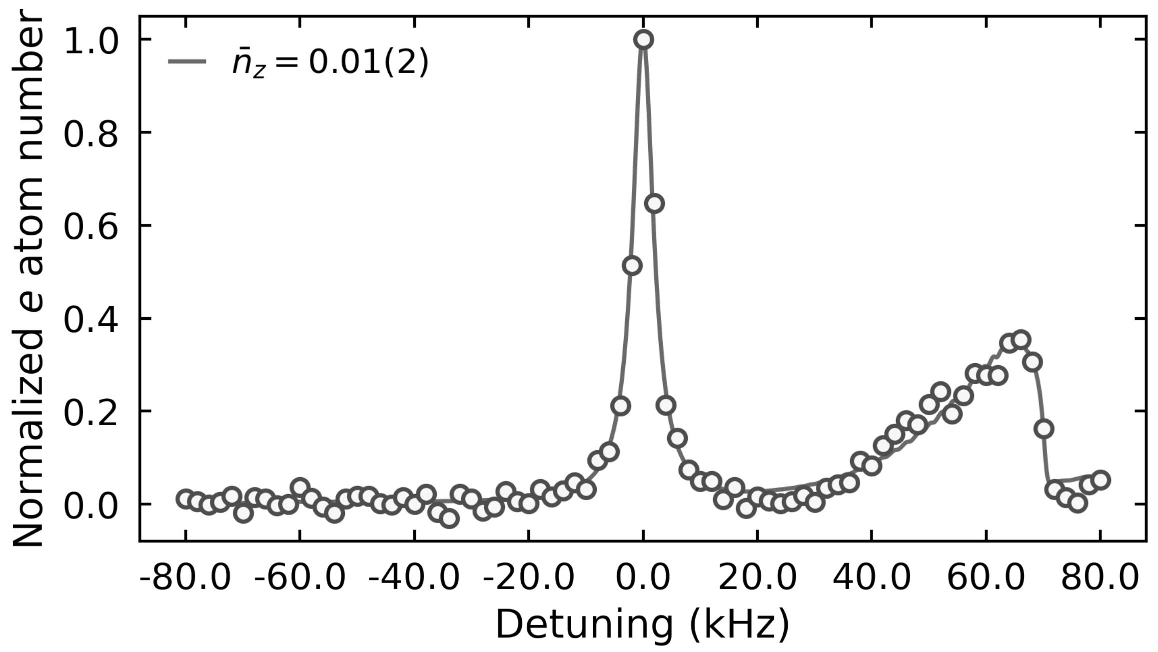

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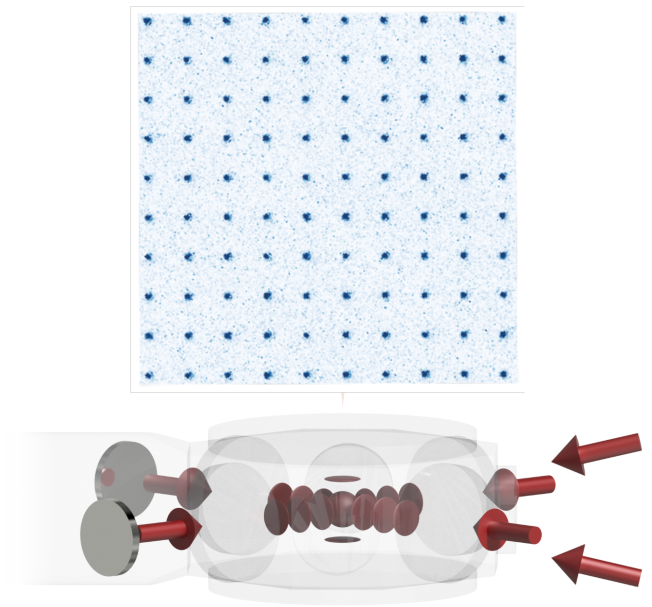

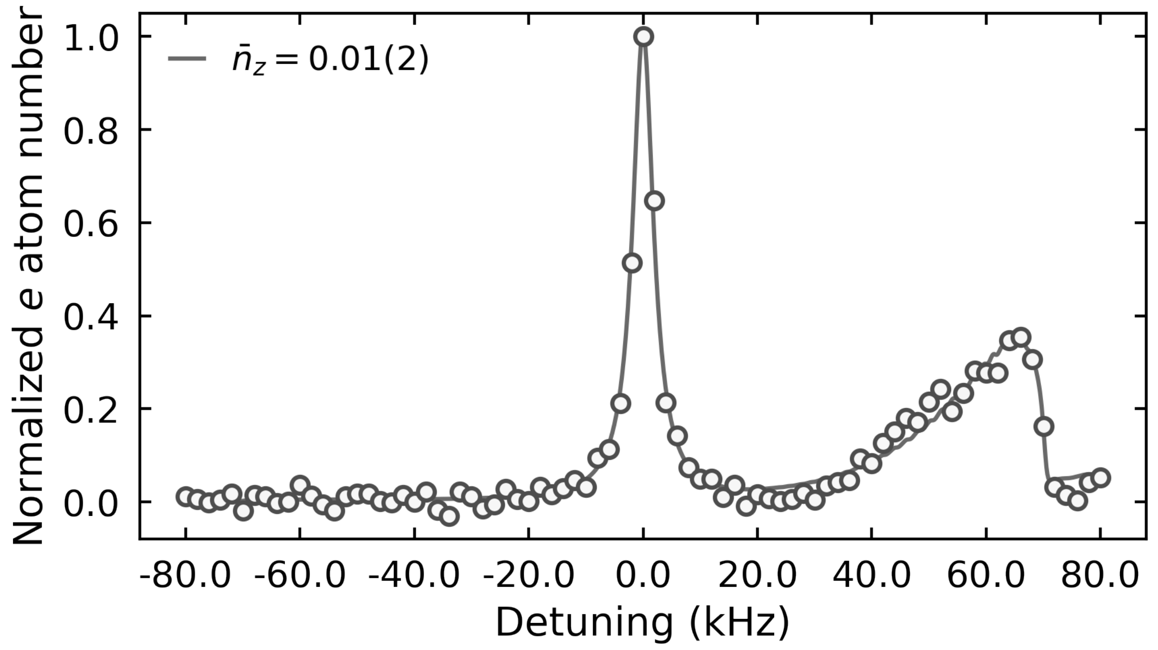

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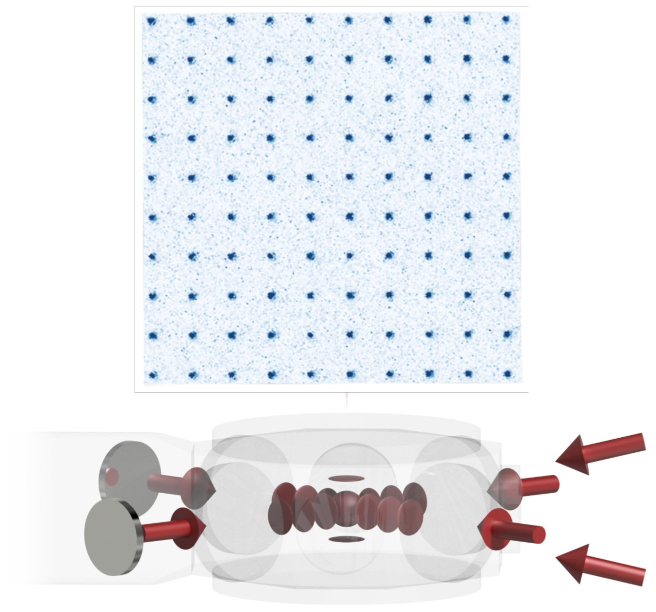

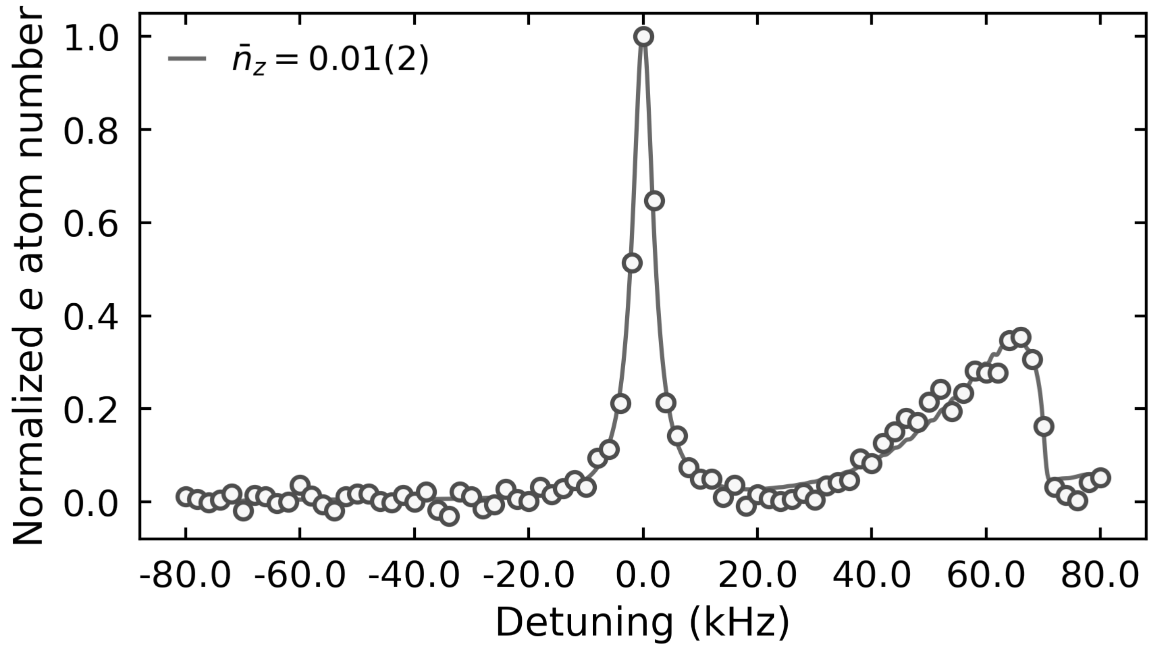

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Next: single-plane loading + single-atom imaging

Höhn, Staub, Brochier, Darkwah Oppong, Aidelsburger, Phys. Rev. A **108**, 053325 (2023)
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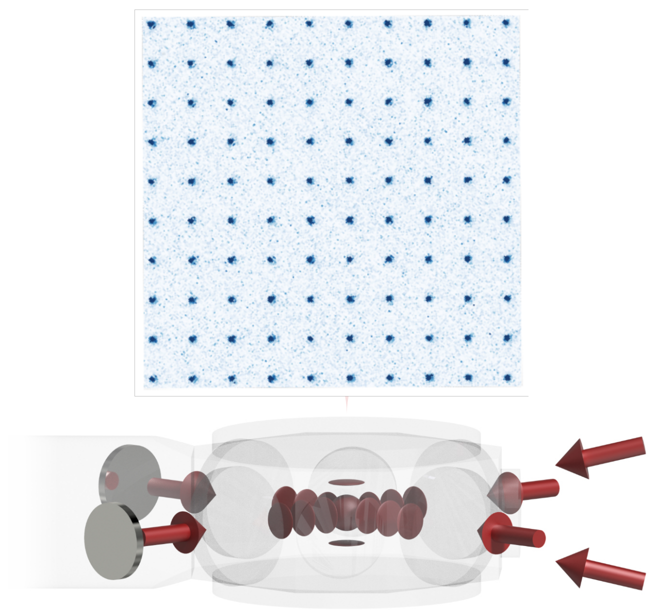

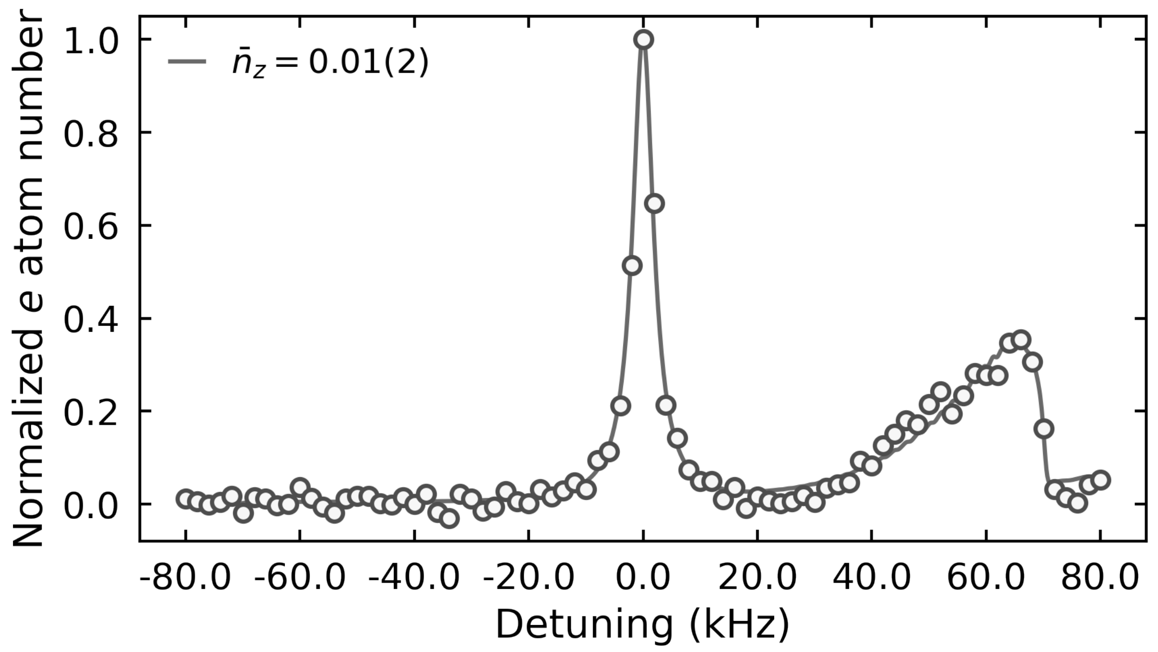

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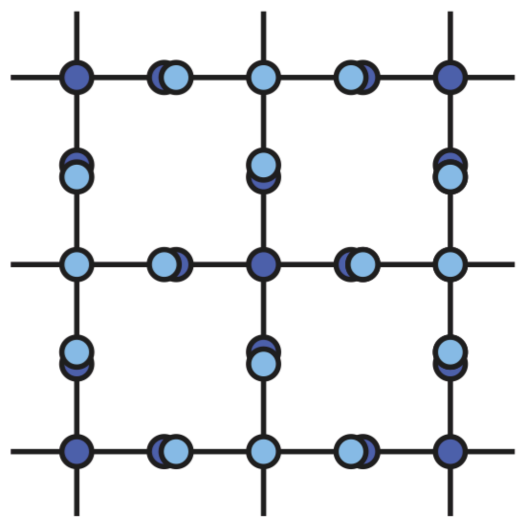
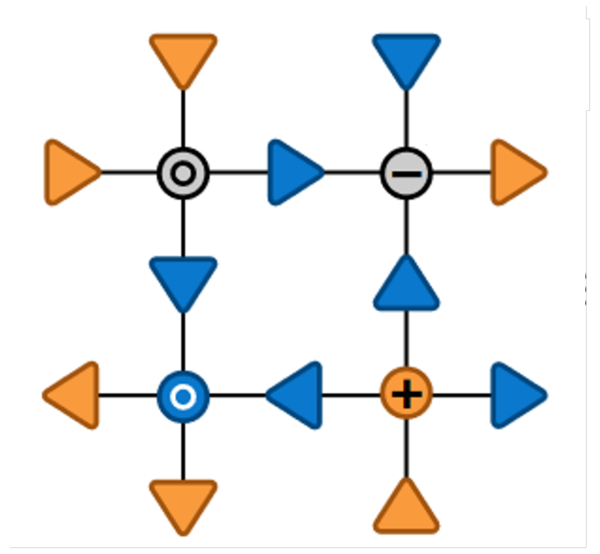
Outlook: Simulating U(1) LGTs with fermionic Yb





- 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)

Höhn, Staub, Brochier, Darkwah Oppong, Aidelsburger, Phys. Rev. A **108**, 053325 (2023)
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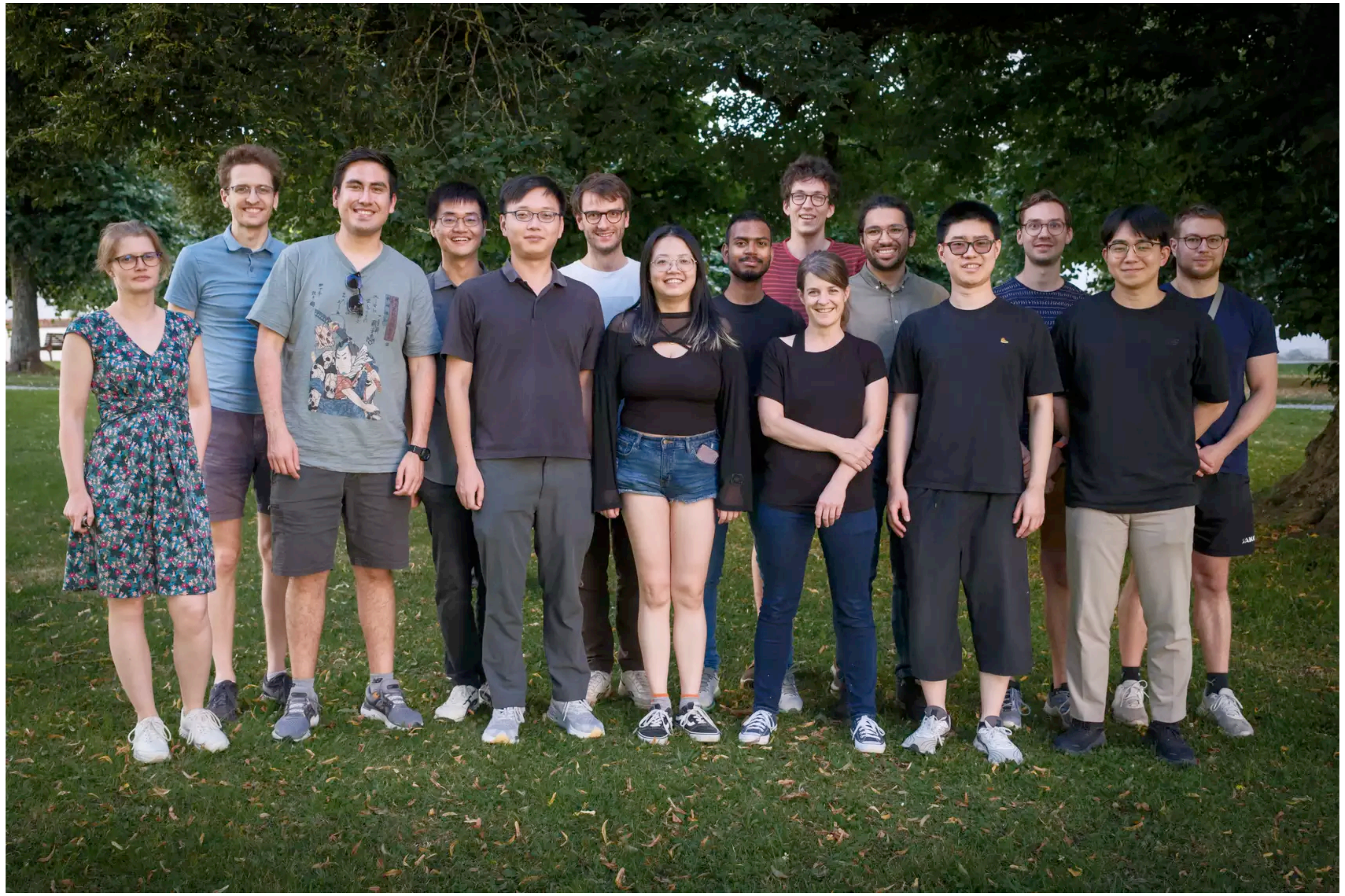
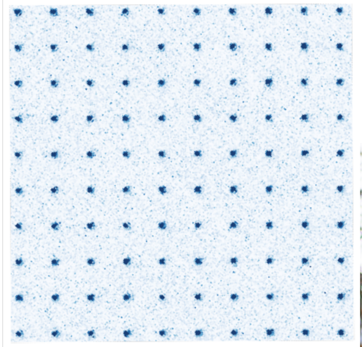
The Team

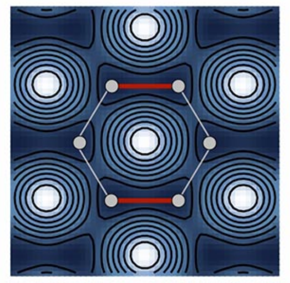
www.mpq.mpg.de/eng-quantum-systems

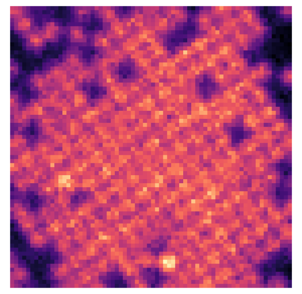




Yb hybrid tweezer-lattice

Tim Höhn, Etienne Staub, MA, Ronen Kroeze,
Leonardo Bezzo, René Villela, Er Zu (Aki)

 **K honeycomb lattice**

 **Cs Quantum Gas Microscope**

Ryd-Yb

Yb double-frequency clock

Thank you