Revealing Quantum Statistics with a Pair of Distant Atoms

presented by

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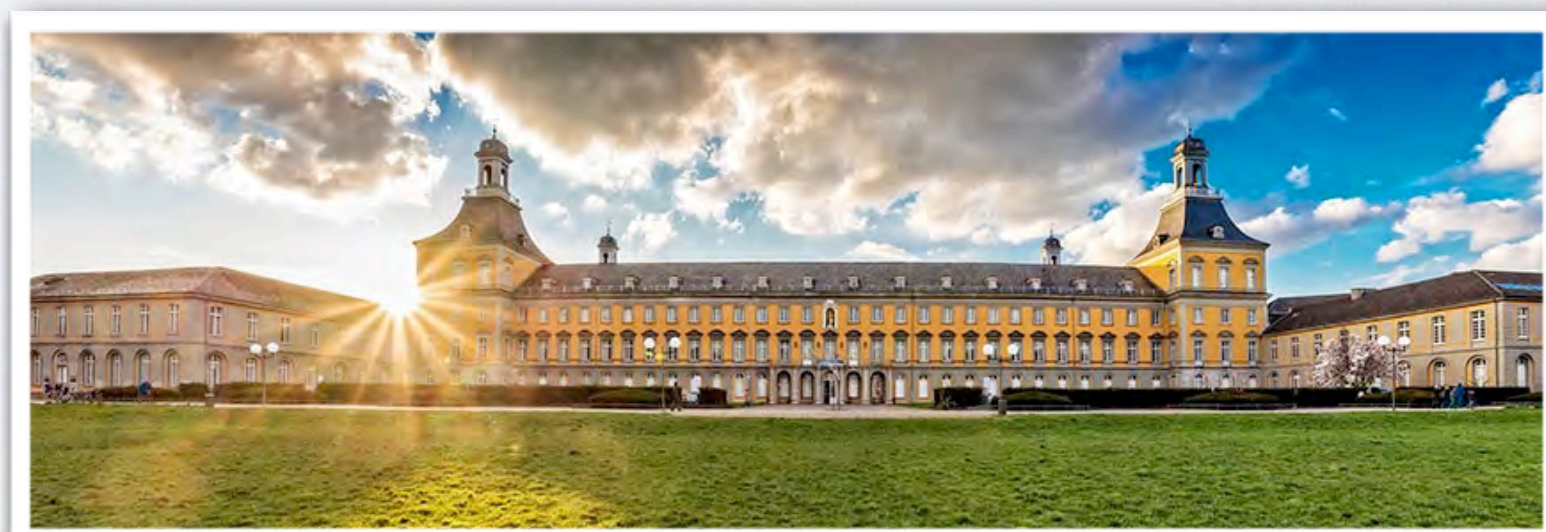
Institut für Angewandte Physik – Universität Bonn
http://quantum-technologies.iap.uni-bonn.de/alberti

INFN - Laboratori Nazionali di Frascati
Is quantum theory exact? The quest for the spin-statistics connection violation

5th June 2018



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Ministerium für Innovation, Wissenschaft und Forschung des Landes Nordrhein-Westfalen
Nachwuchsgruppe in Nanotechnologie

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Identity of indiscernibles

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Gottfried Wilhelm Leibniz (1646–1716)

"… it is never true that two substances are entirely alike, differing only in being two rather than one. …"

G. W. Leibniz , "Discourse on Metaphysics," section 9 (1686)

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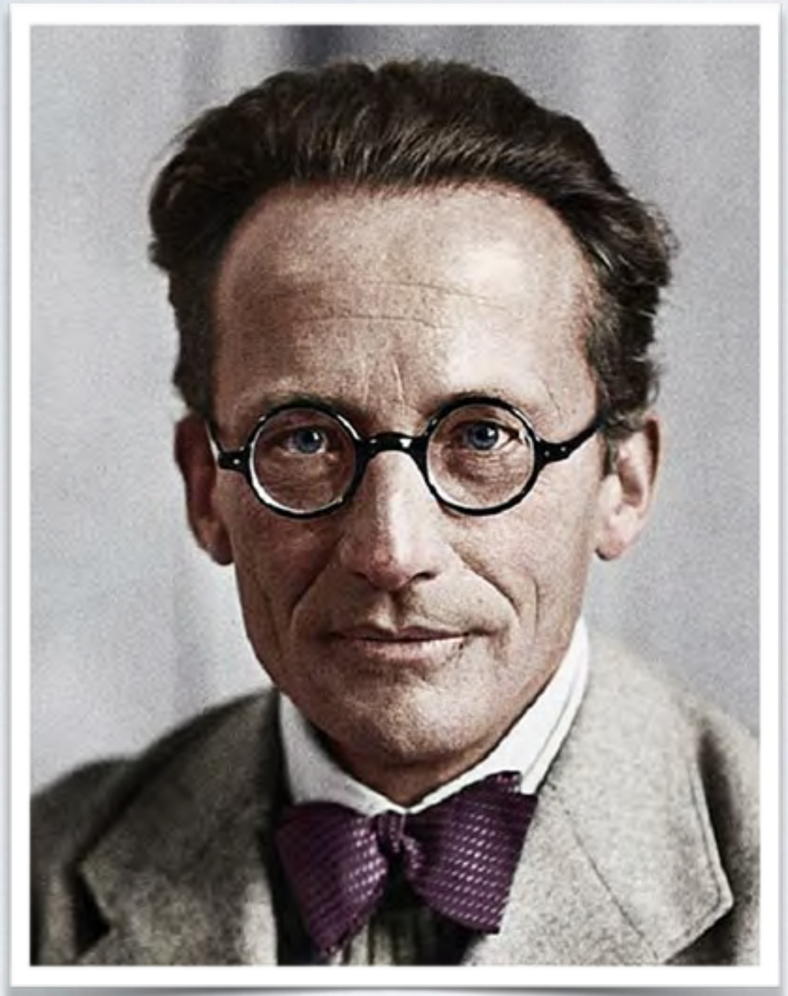

Erwin Schrödinger (1887–1961)

“… it is not a question of being able to ascertain the identify in some instances and not being able to do so in others. It is beyond doubt that the question of the `sameness’ of identity really and truly has no meaning.“

E. Schrödinger, “Science and Humanism” 1952

Hong-Ou-Mandel interference

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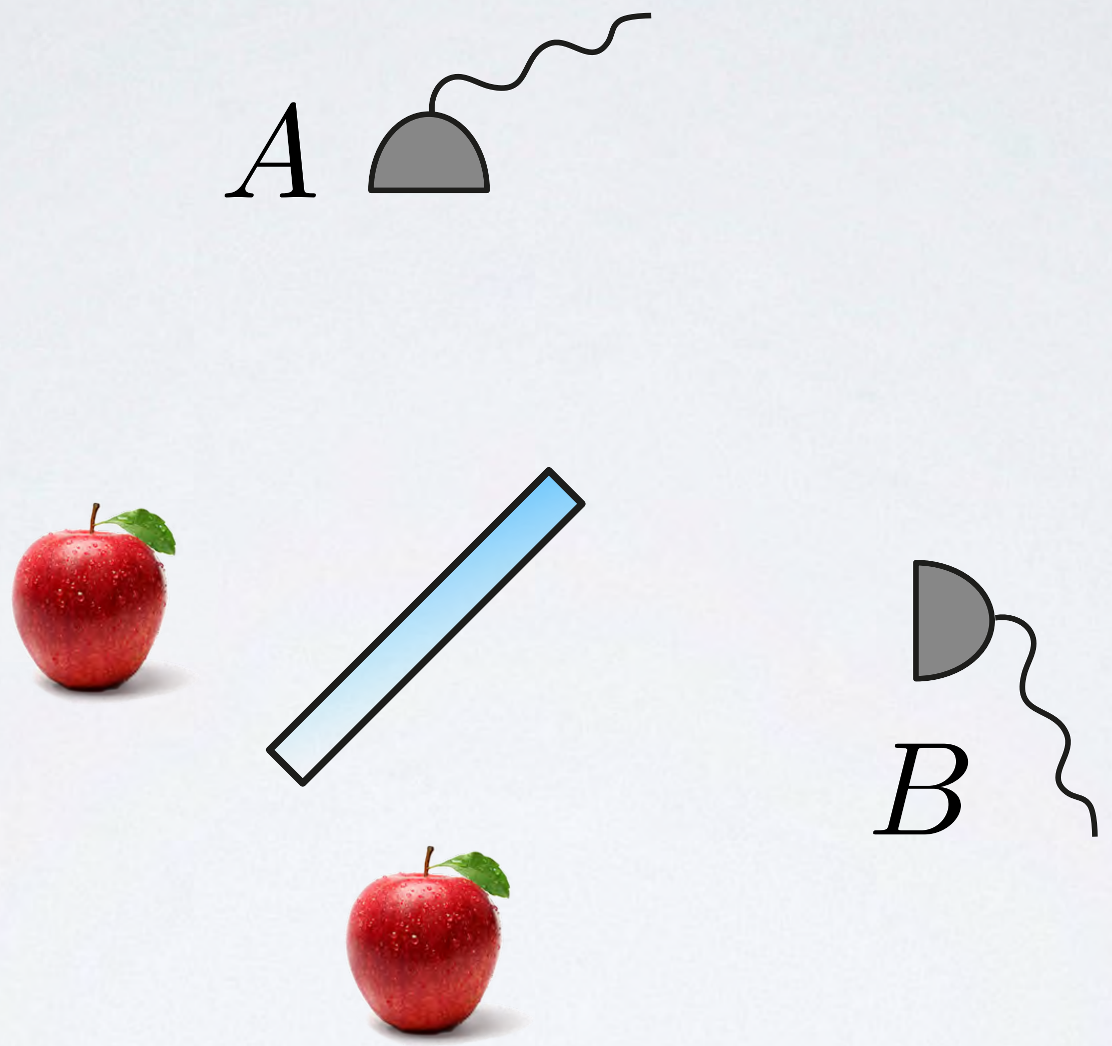
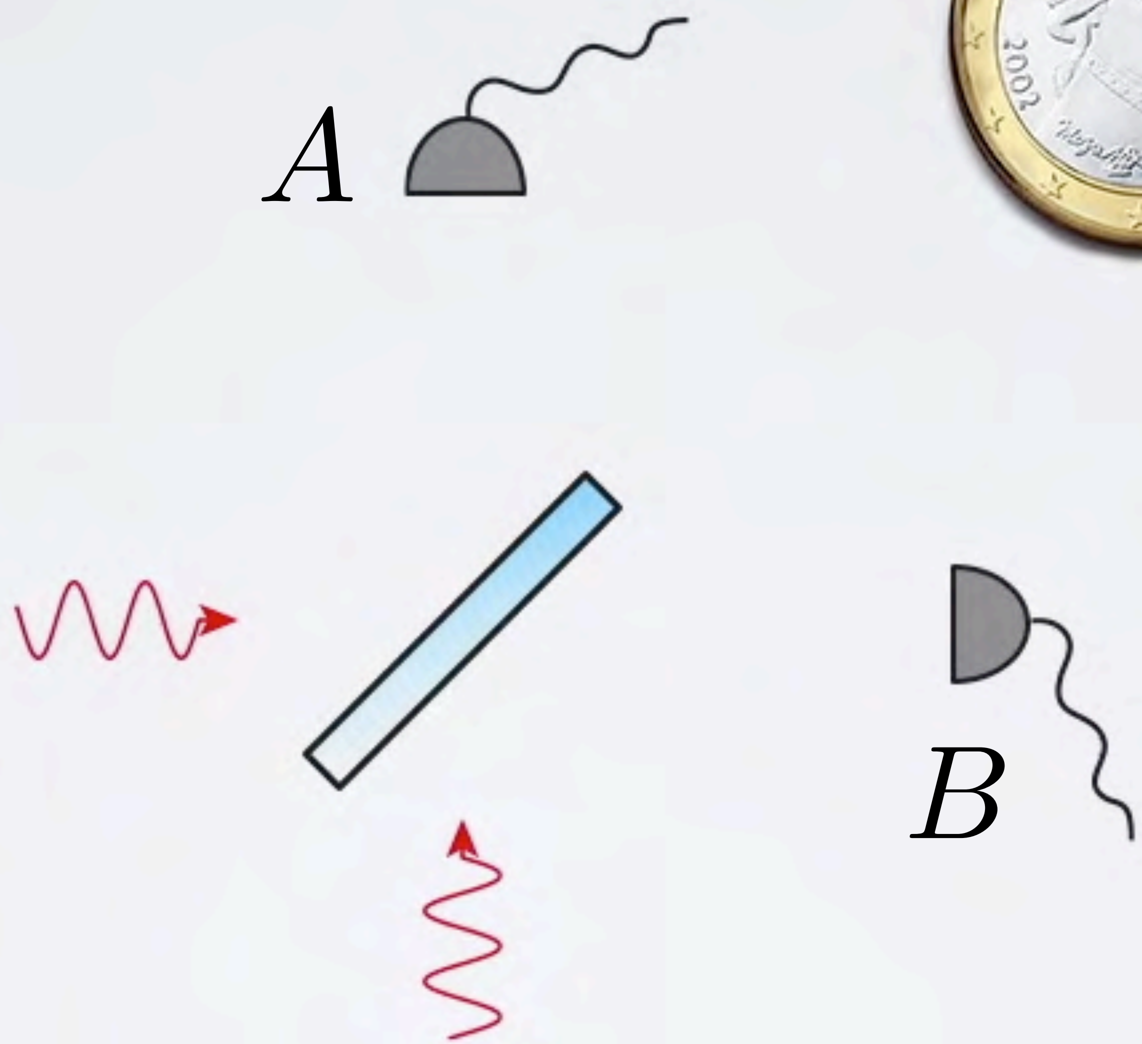
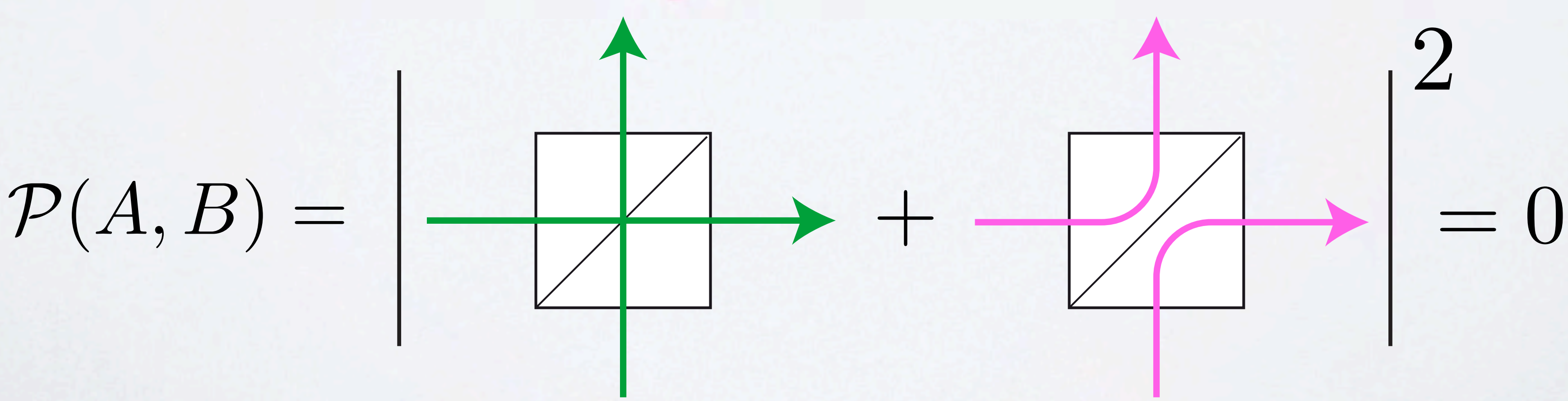
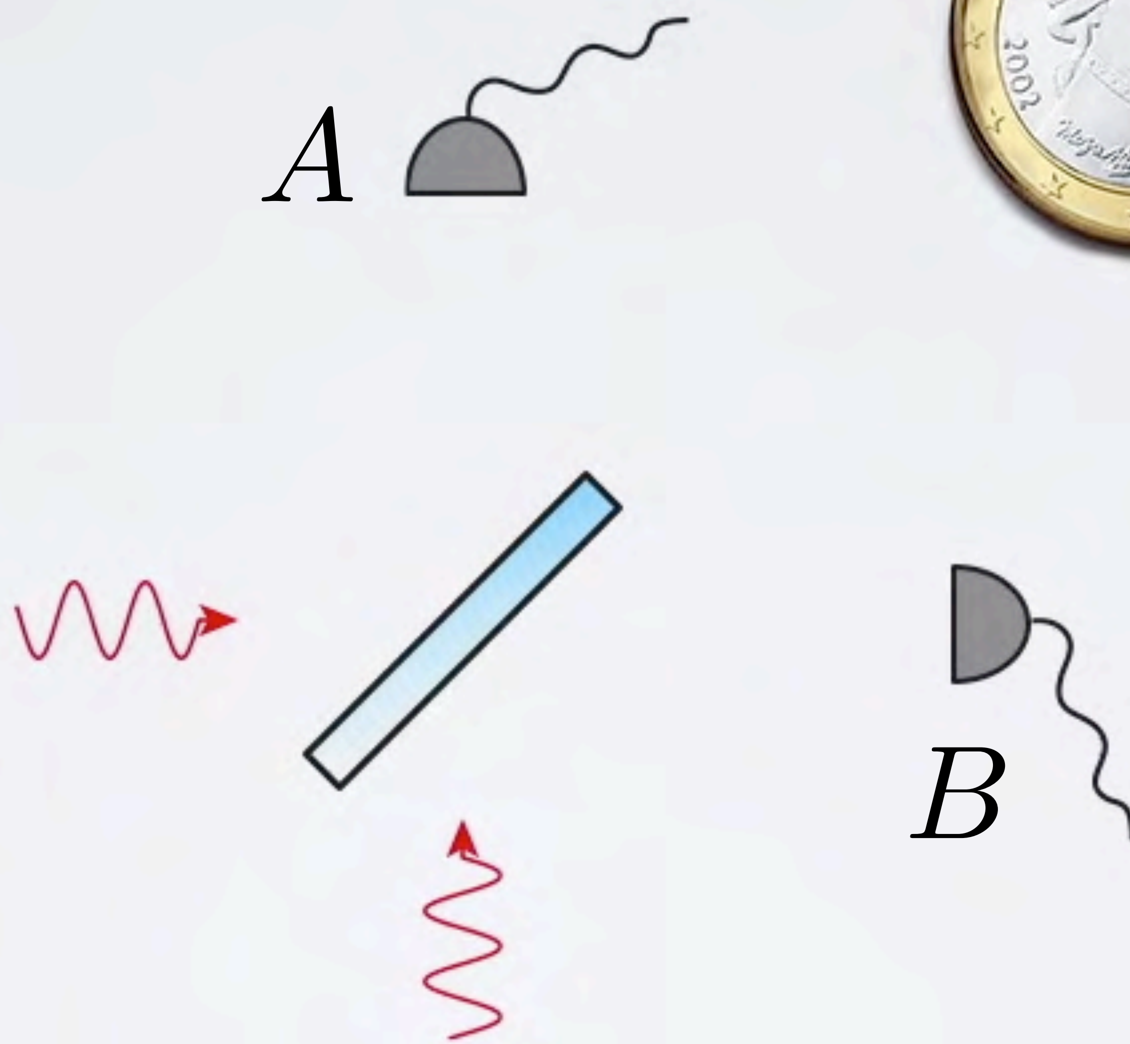


Hong-Ou-Mandel interference





Hong-Ou-Mandel interference



$$|\mathrm{NOON}\rangle = \frac{1}{\sqrt{2}}\Big(\frac{a_A^{\dagger\,2}}{\sqrt{2}} - \frac{a_B^{\dagger\,2}}{\sqrt{2}}\Big)|\mathrm{vac}\rangle$$

Hong-Ou-Mandel-like experiments

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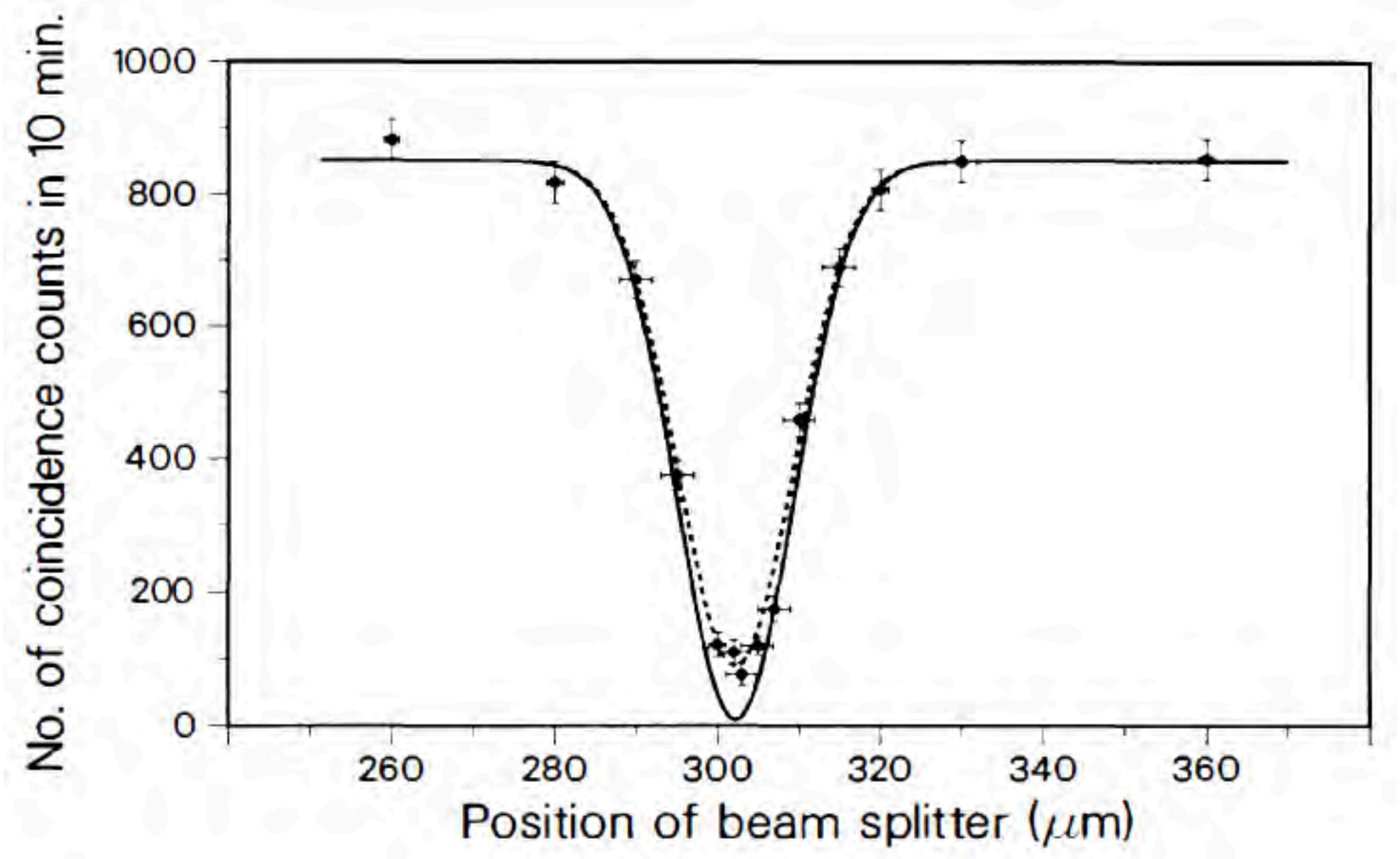
Photons:

C. K. Hong, Z. Y. Ou, and L. Mandel, Measurement of subpicosecond time intervals between two photons by interference, Phys. Rev. Lett. 59, 2044 (1987).



Hong-Ou-Mandel-like experiments

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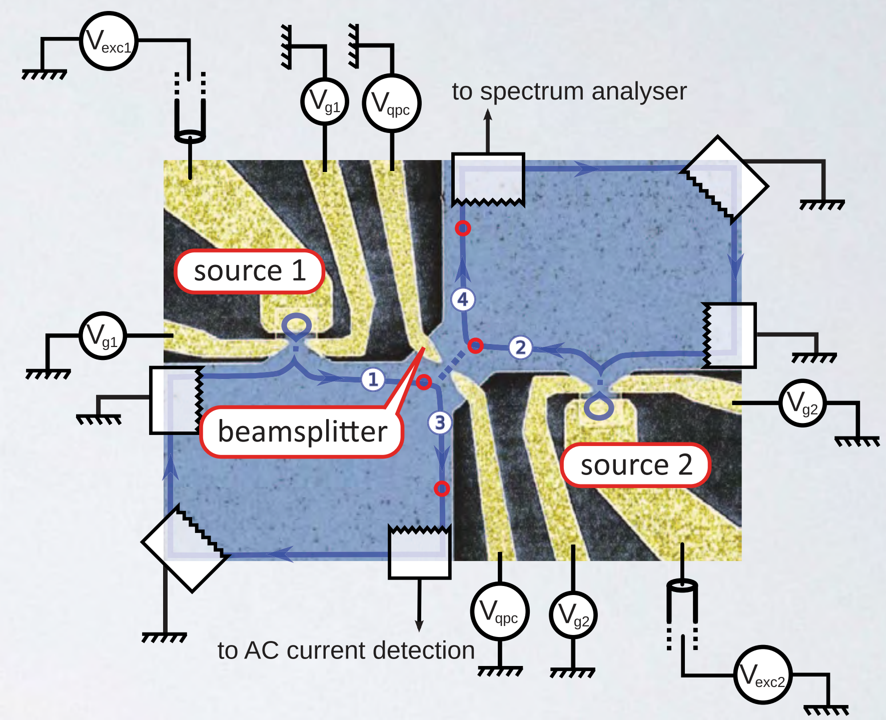
Electrons:

Bocquillon, E. *et al.* Coherence and Indistinguishability of Single Electrons Emitted by Independent Sources. Science **339**, 1054–1057 (2013).



Plasmonic waveguides:

R.W. Heeres, L. P. Kouwenhoven, and V. Zwiller, Quantum interference in plasmonic circuits, Nat. Nanotechnol. **8**, 719 (2013).

Atoms:

A. M. Kaufman, B. J. Lester, C. M. Reynolds, M. L. Wall, M. Foss-Feig, K. R. A. Hazzard, A. M. Rey, and C. A. Regal, Two-particle quantum interference in tunnel-coupled optical tweezers, Science **345**, 306 (2014).

R. Lopes, A. Imanaliev, A. Aspect, M. Cheneau, D. Boiron, and C. I. Westbrook, Atomic Hong–Ou–Mandel experiment, Nature **520**, 66 (2015).

Phonons:

K. Toyoda, R. Hiji, A. Noguchi, and S. Urabe, Hong–Ou–Mandel interference of two phonons in trapped ions, Nature **527**, 74 (2015).

Optical lattice potentials

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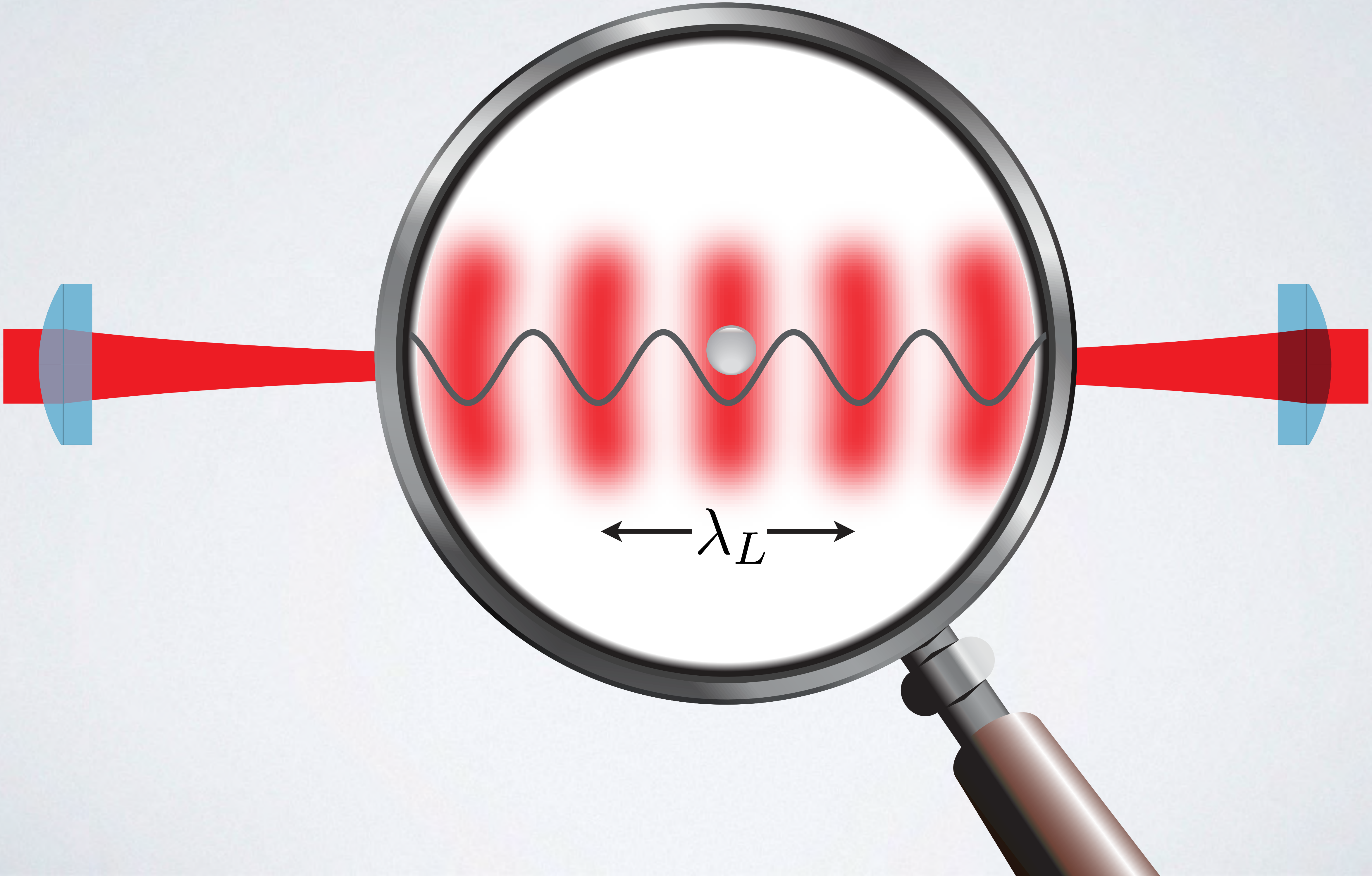
$$\mathcal{H} = \frac{p^2}{2m} - U_0 \cos^2(k_L x) \qquad (k_L = 2\pi/\lambda_L)$$



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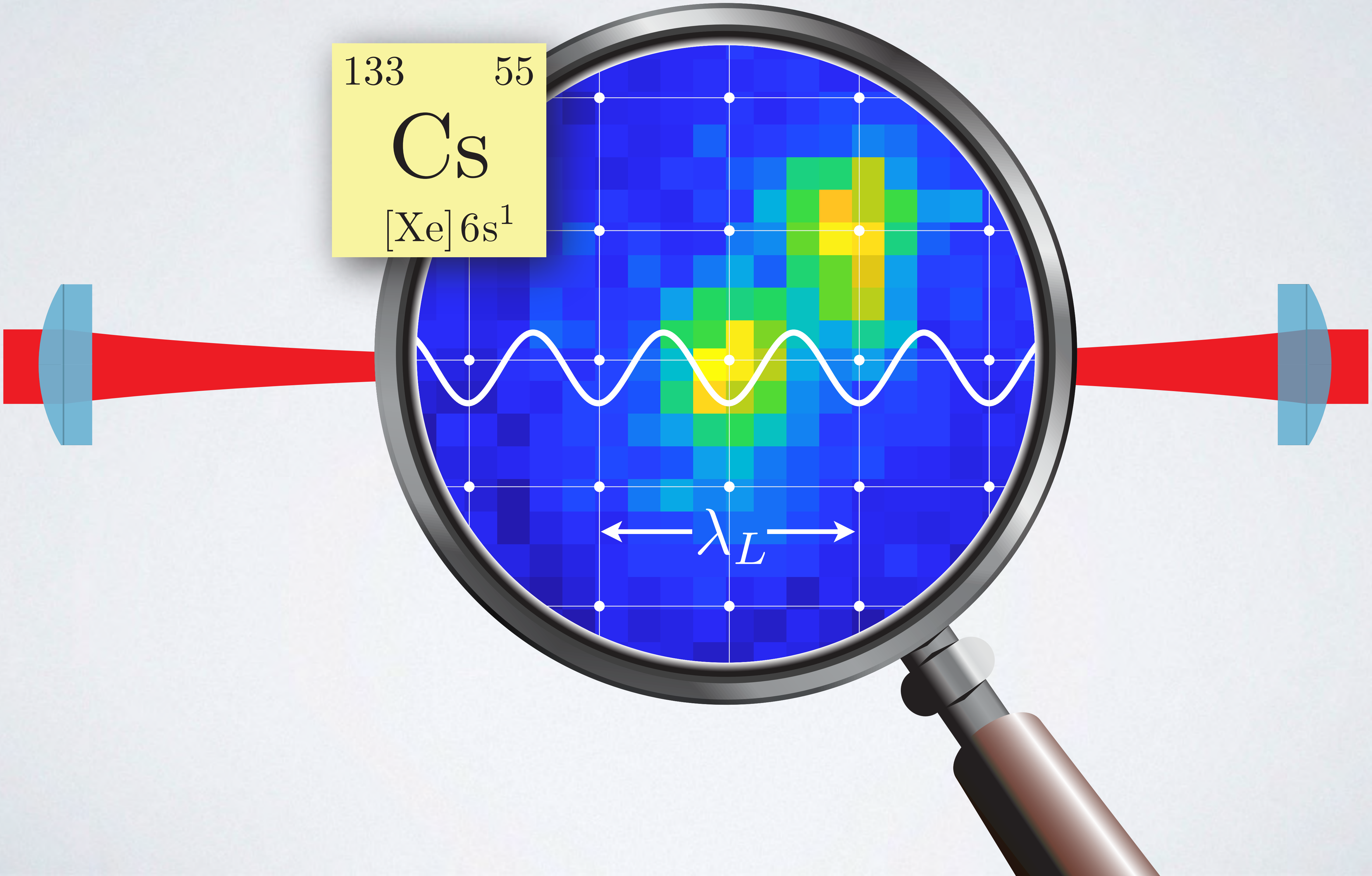

State-dependent optical lattices

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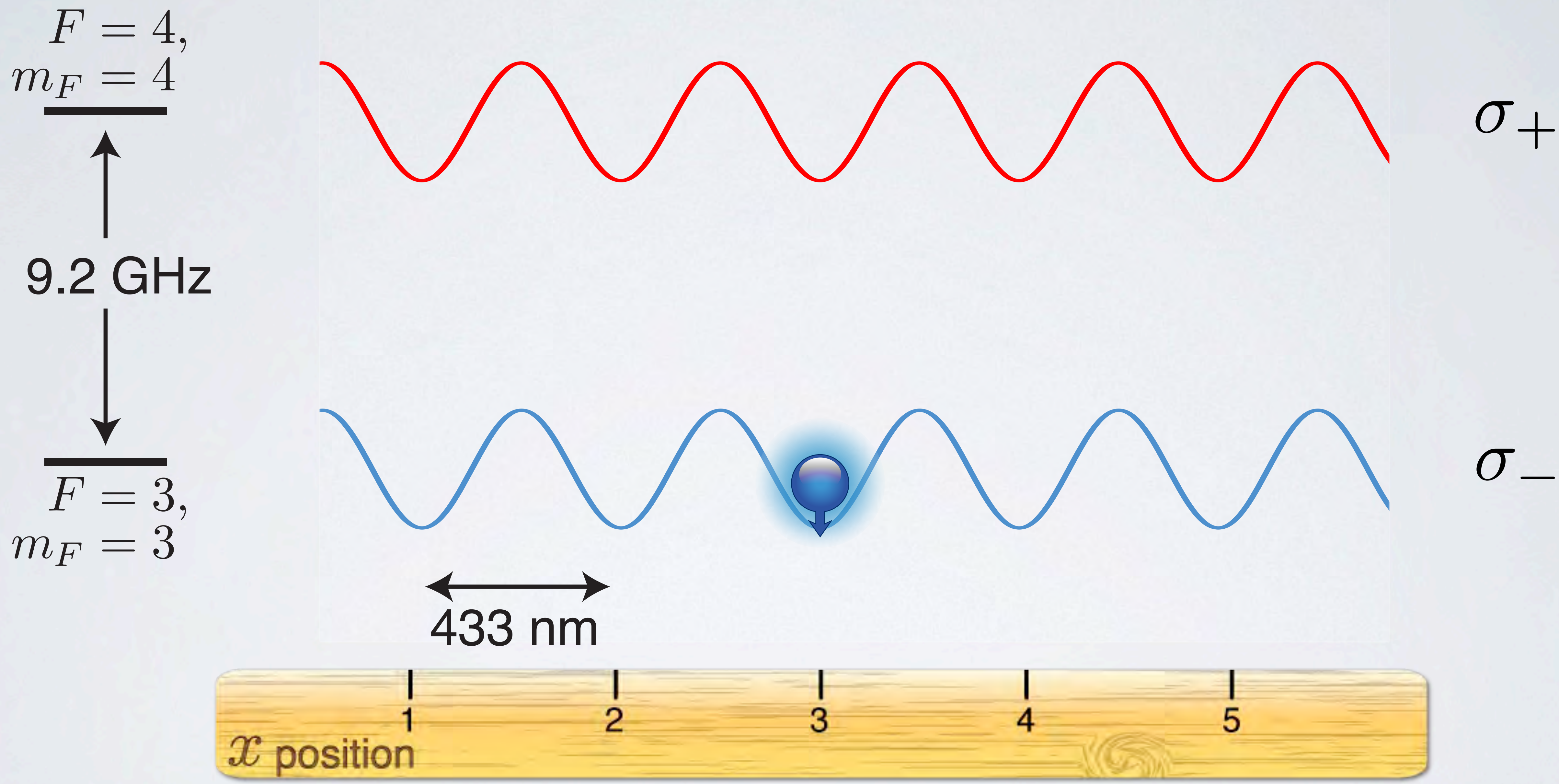
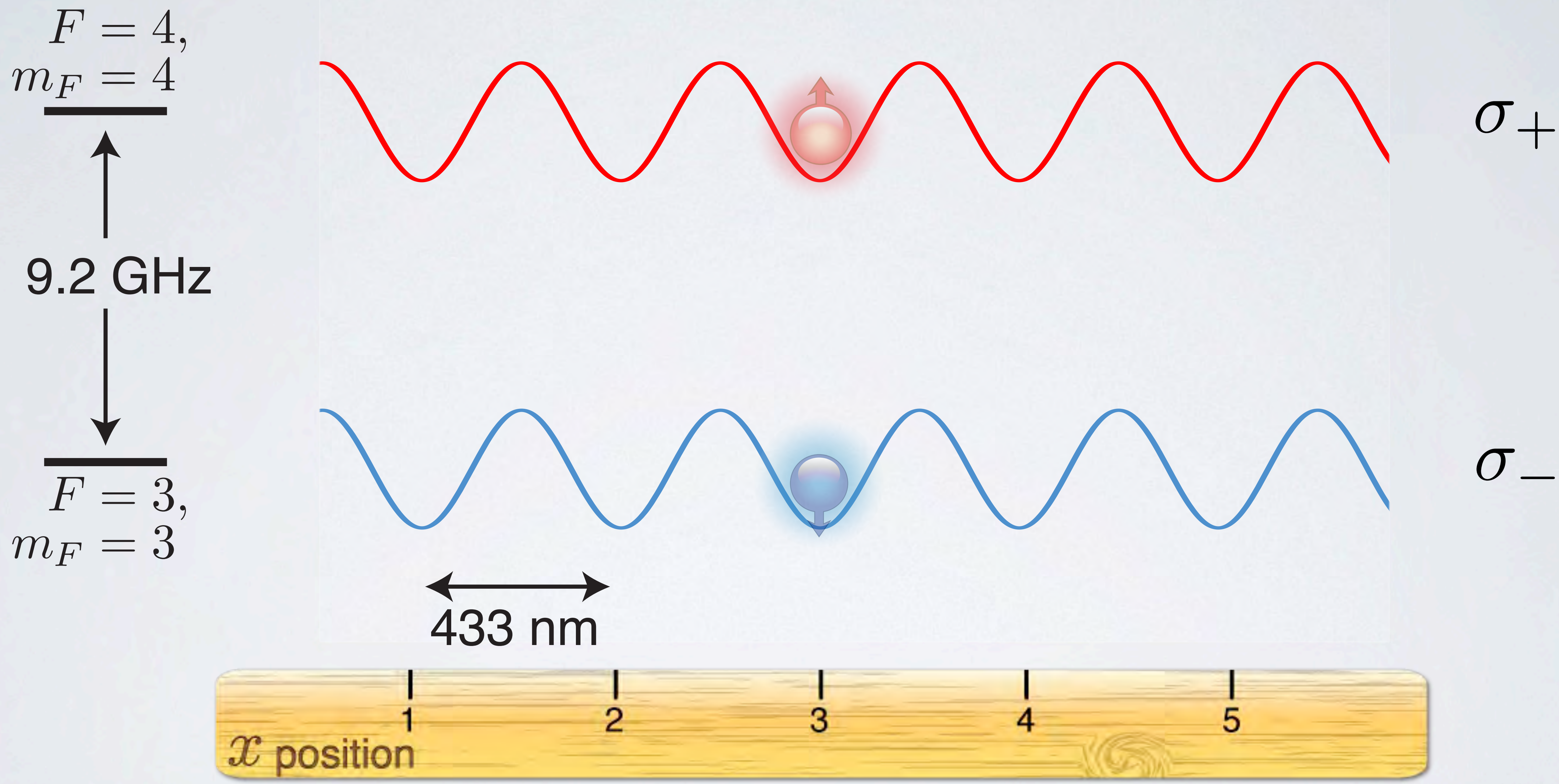


C. Robens, S. Brakhane, W. Alt, D. Meschede, J. Zopes, and A. Alberti, "Fast, high-precision optical polarization synthesizer for ultracold-atom experiments," Phys. Rev. Applied, **9**, 034016 (2018)

State-dependent optical lattices



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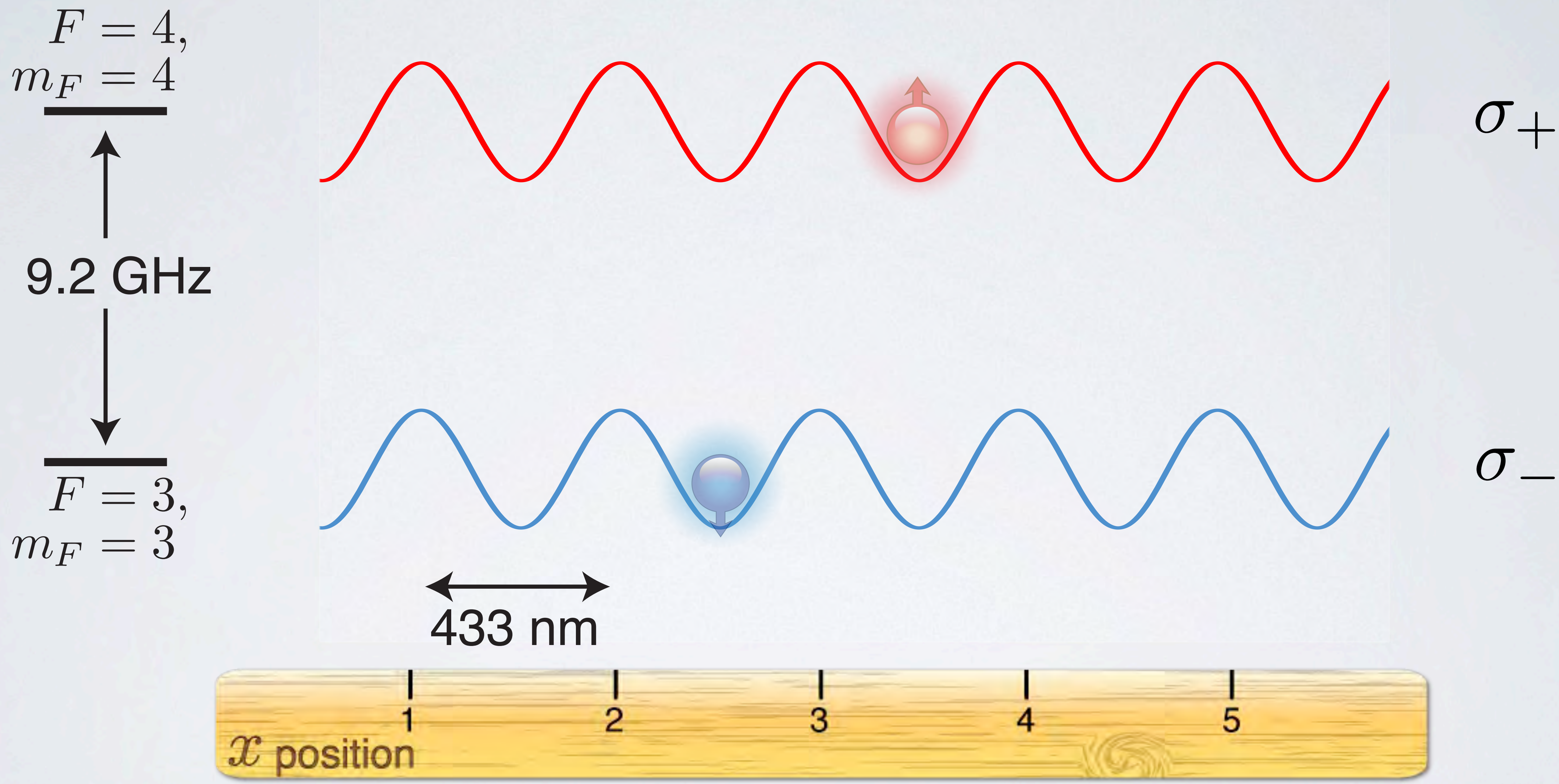

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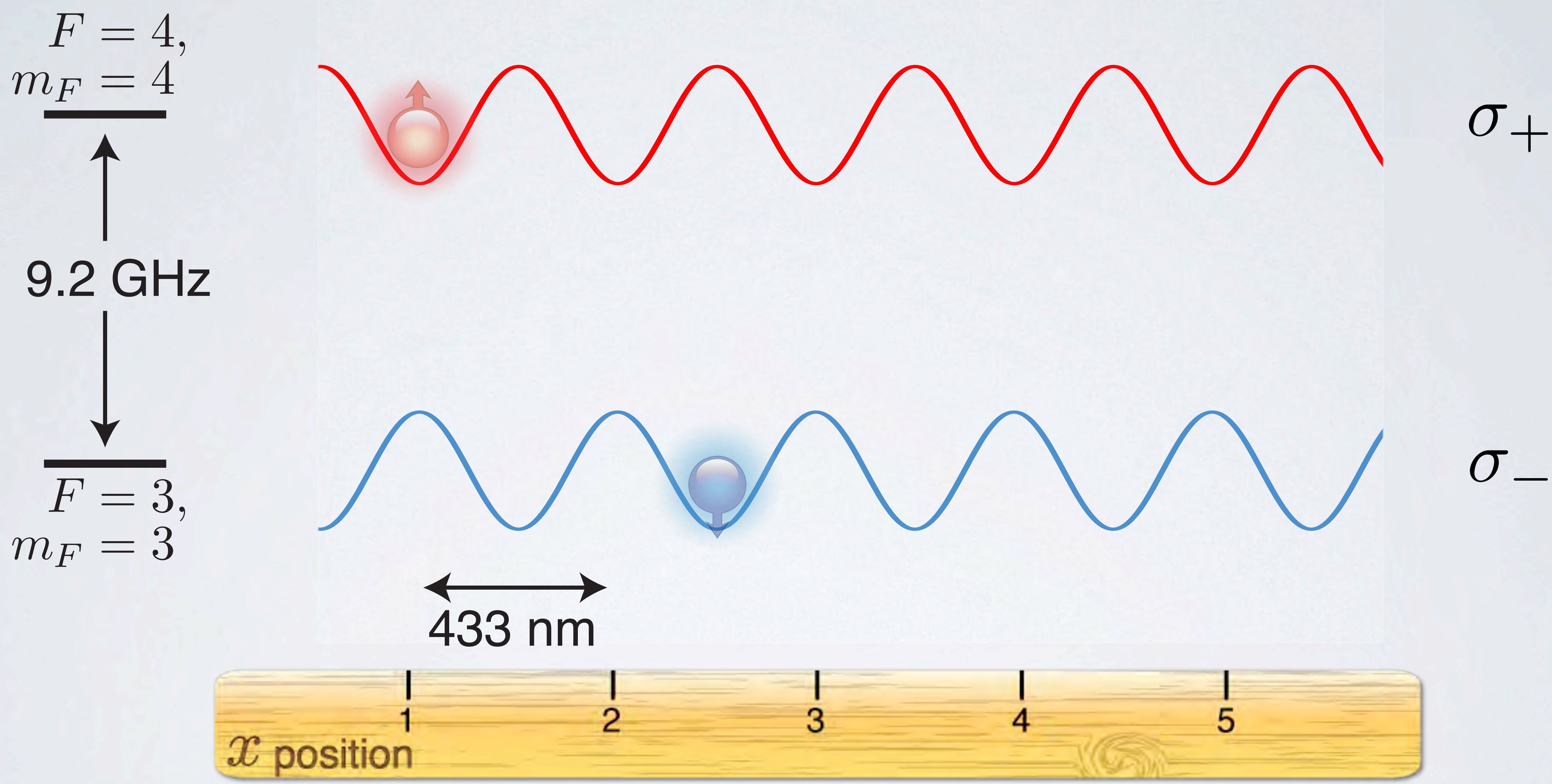

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Polarization-synthesized optical lattice

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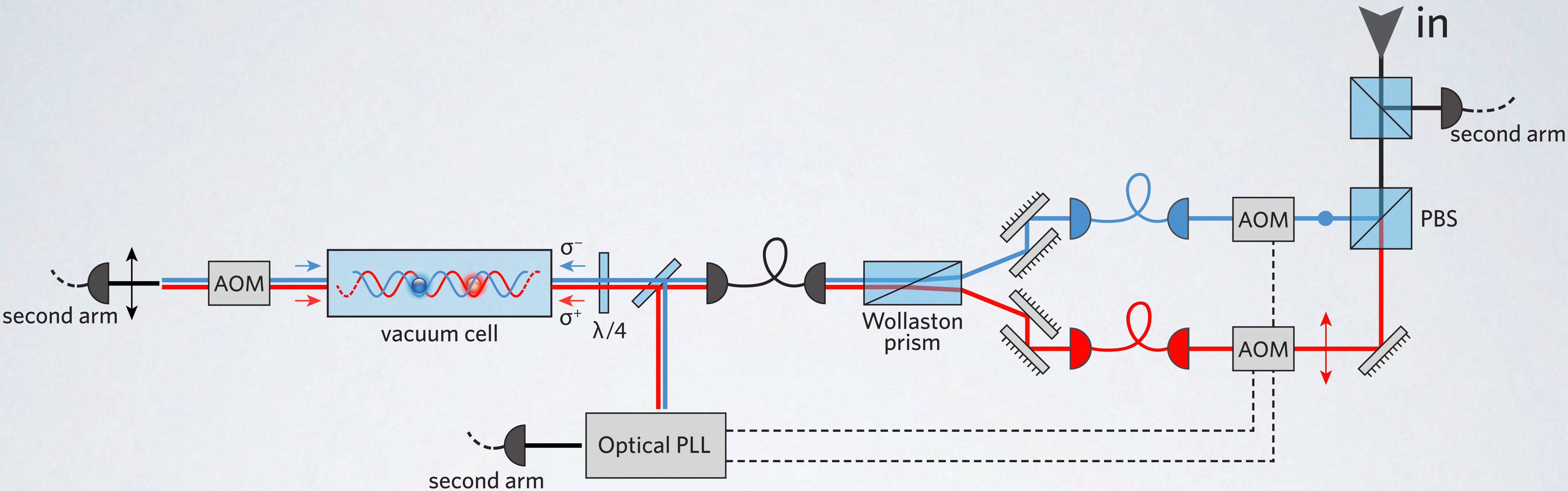

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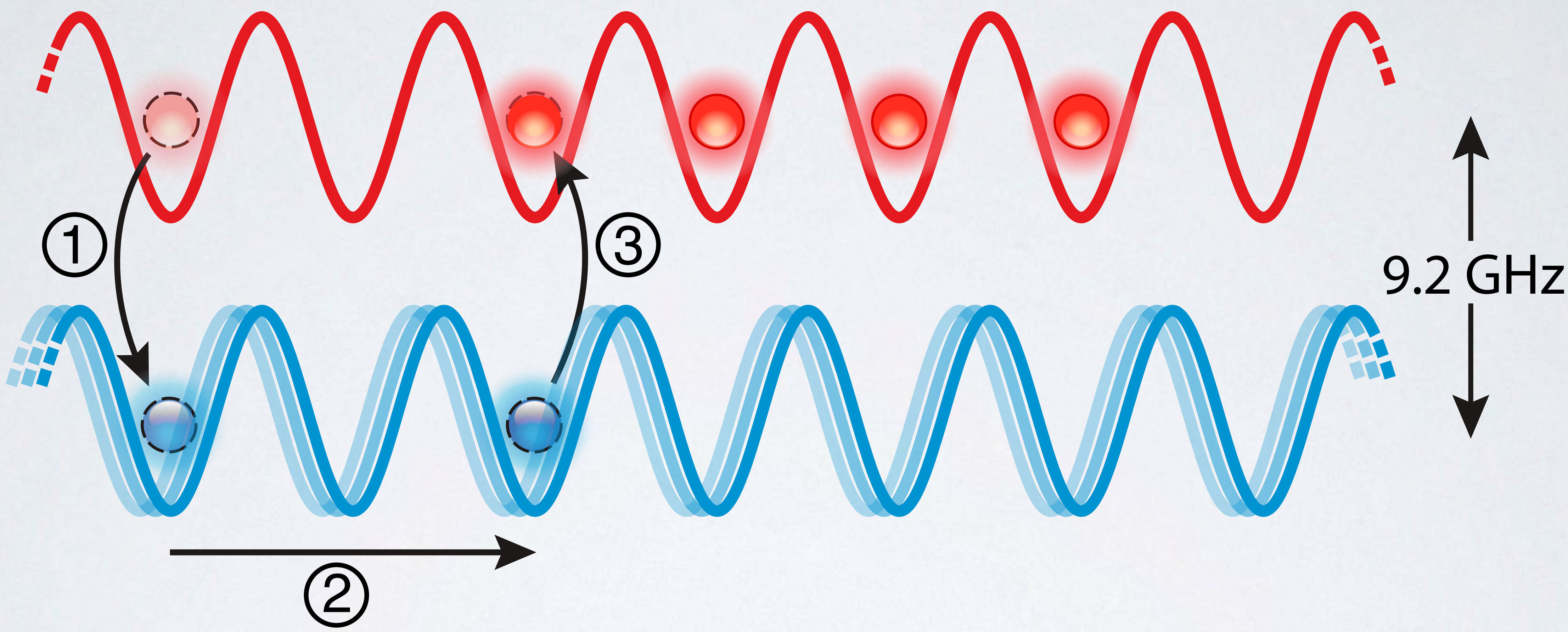
Bottom-up approach to low-entropy states



- C. Robens, J. Zopes, W. Alt, S. Brakhane, D. Meschede, and A. Alberti, "Low-Entropy States of Neutral Atoms in Polarization-Synthesized Optical Lattices," Phys. Rev. Lett. **118**, 065302 (2017).

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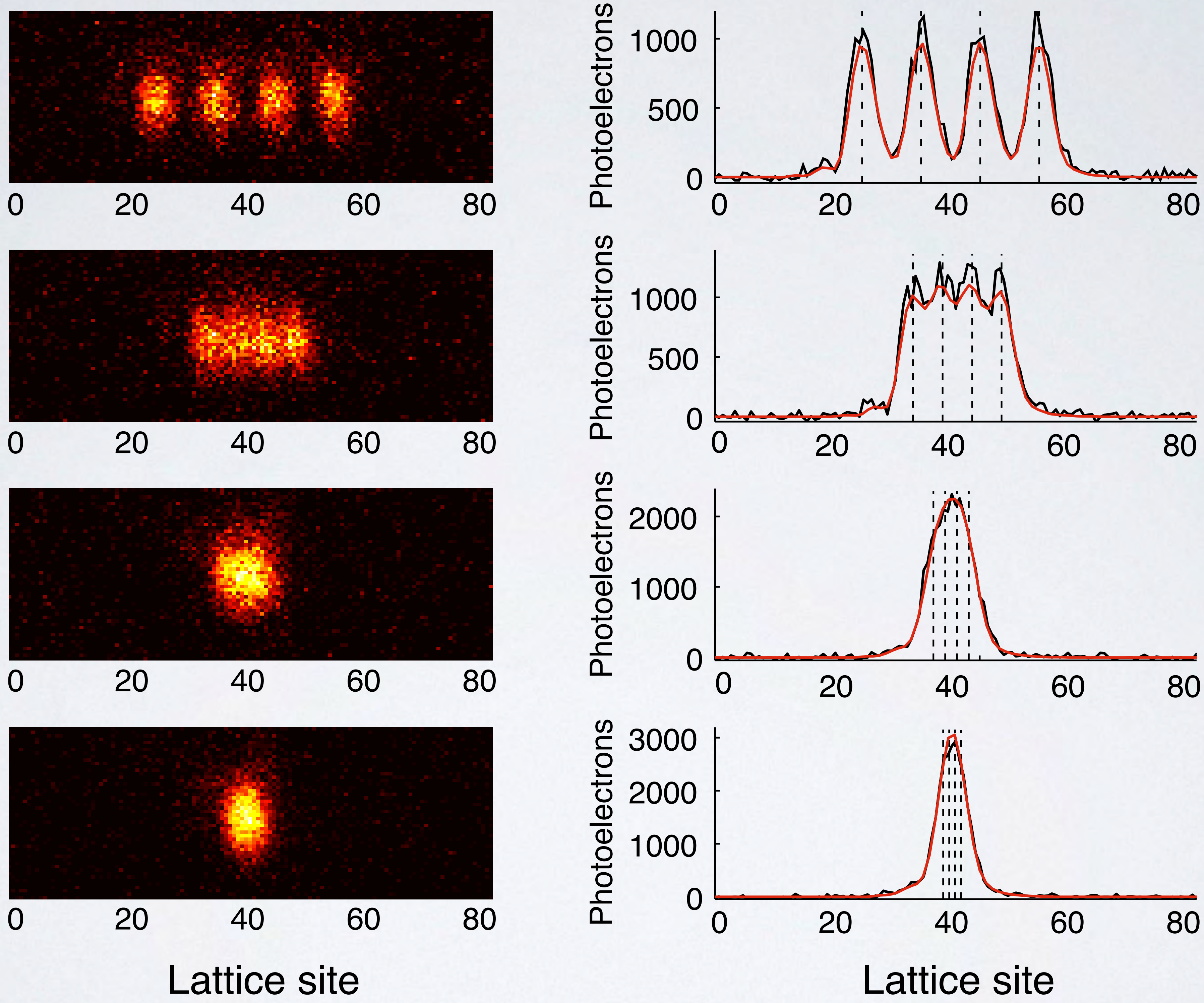

Carsten Robens, et al., "Low-entropy states of neutral atoms in polarization-synthesized optical lattices", Phys. Rev. Lett. 118, 065302 (2017).

Microwave sideband cooling

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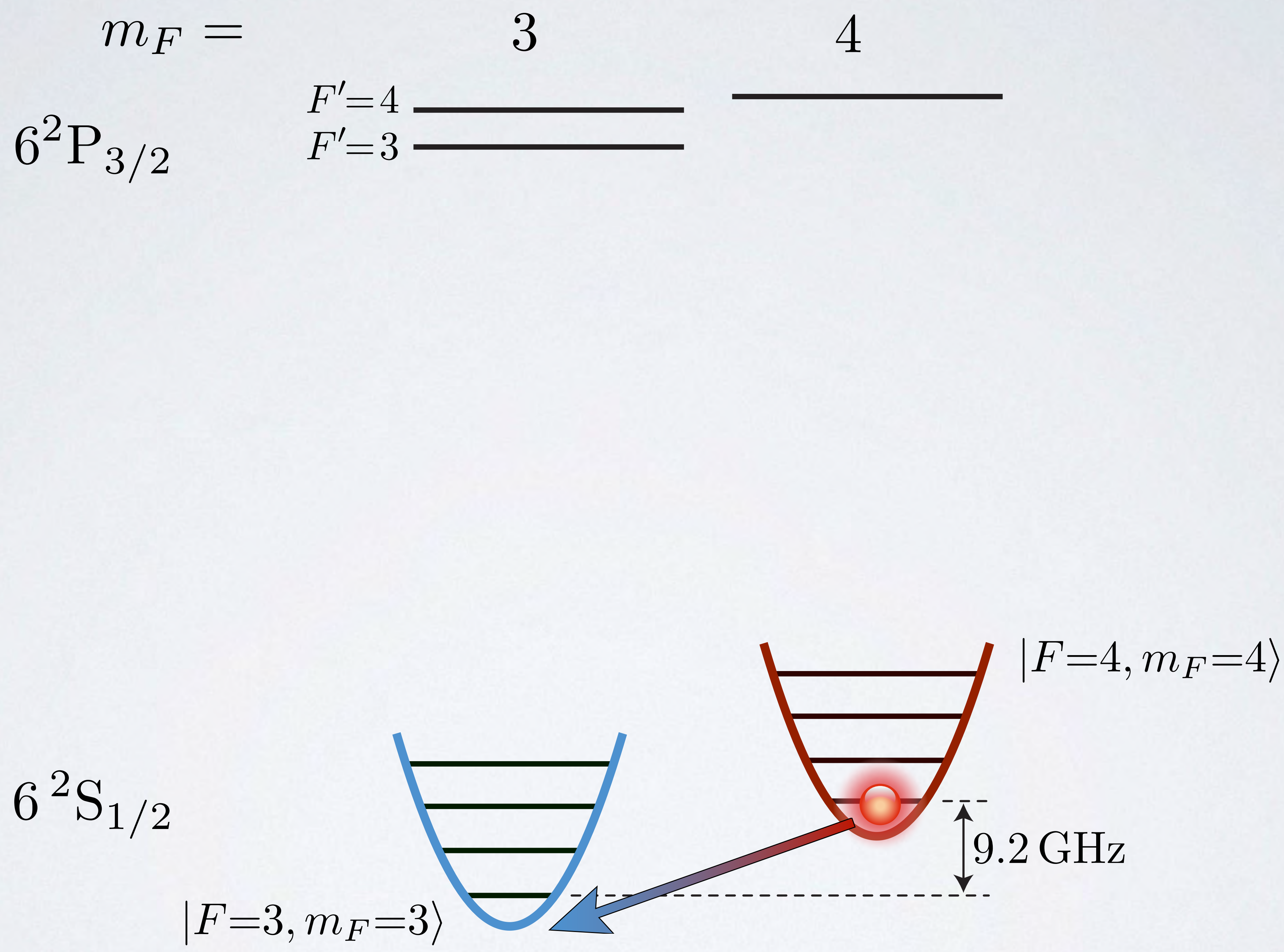

- F. Mintert and C. Wunderlich, Phys. Rev. Lett. **87**, 257904 (2001)
- N. Belmechri, L. Förster, W. Alt, A. Widera, D. Meschede, and A. Alberti, J. Phys. B: At. Mol. Phys. **46**, 104006 (2013)

Microwave sideband spectrum
– before sideband cooling –

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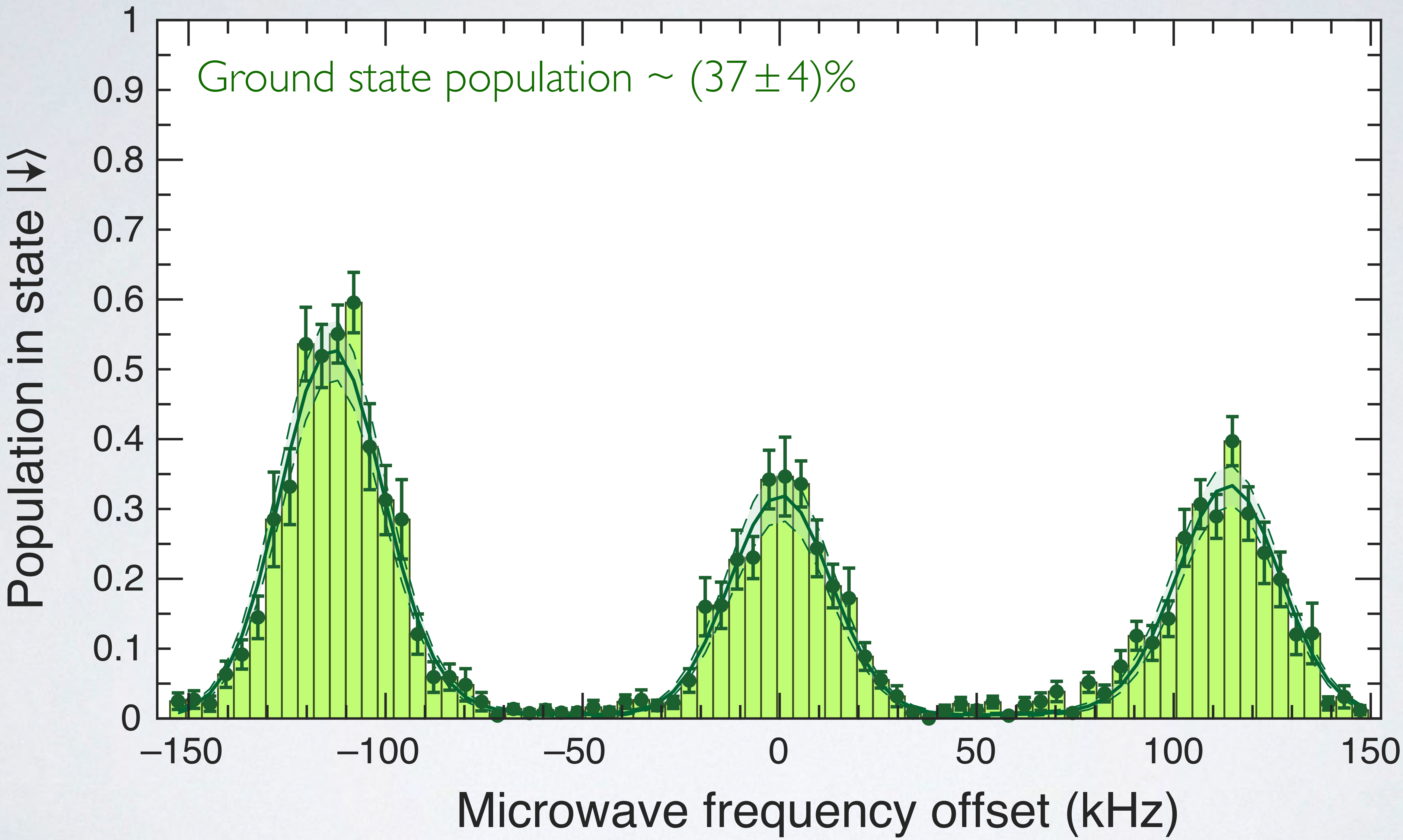

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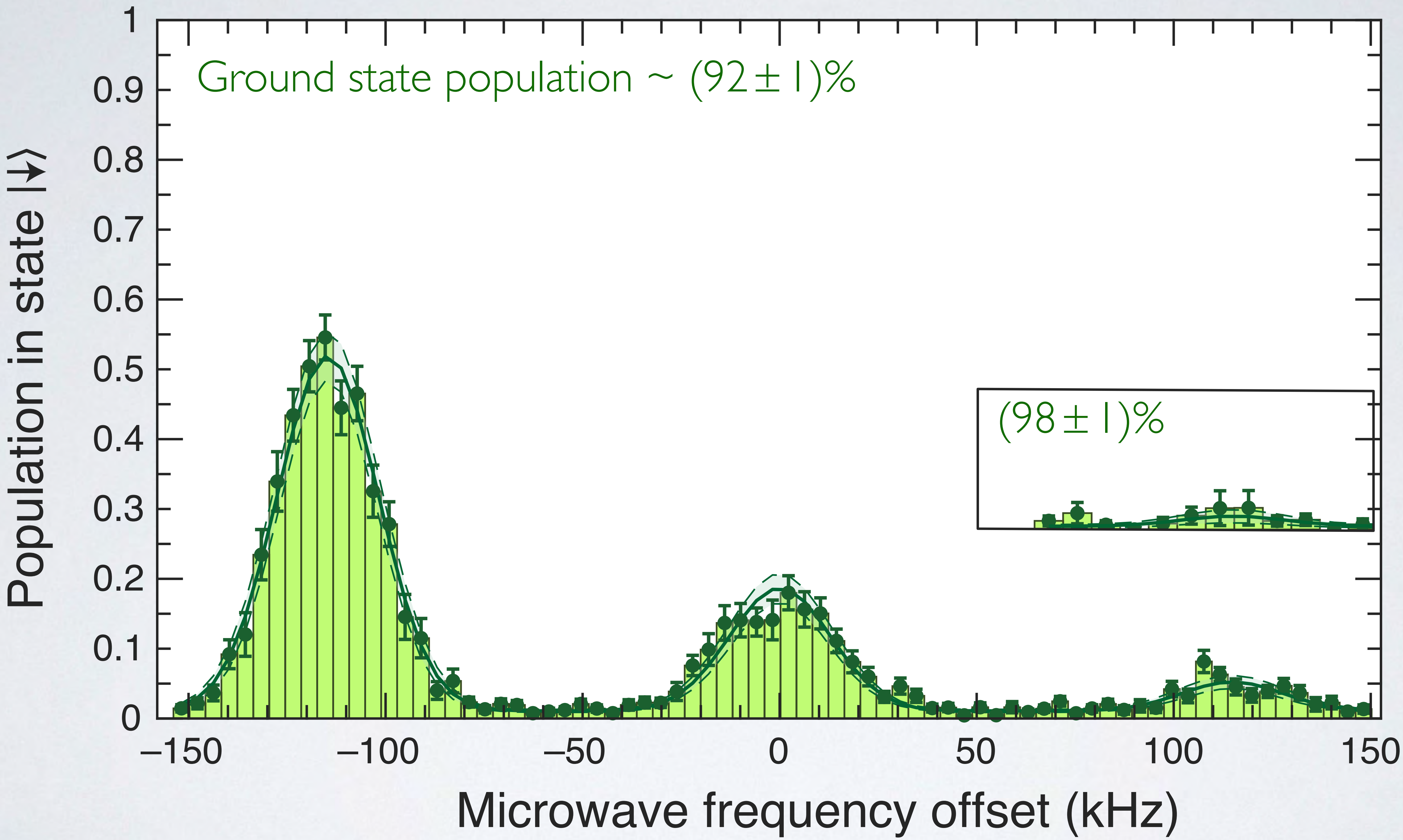

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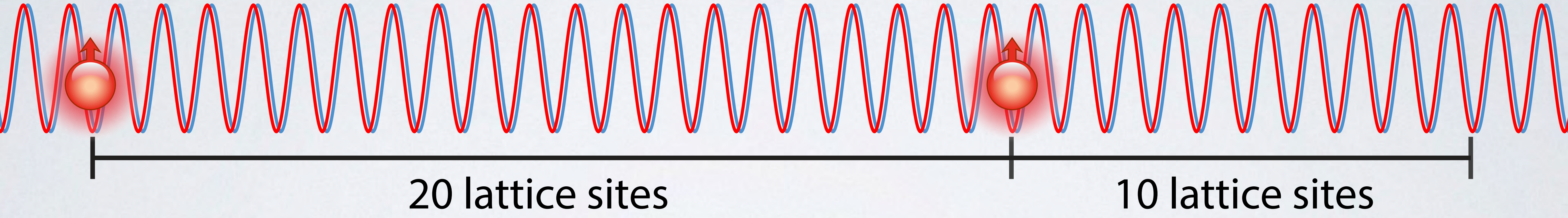

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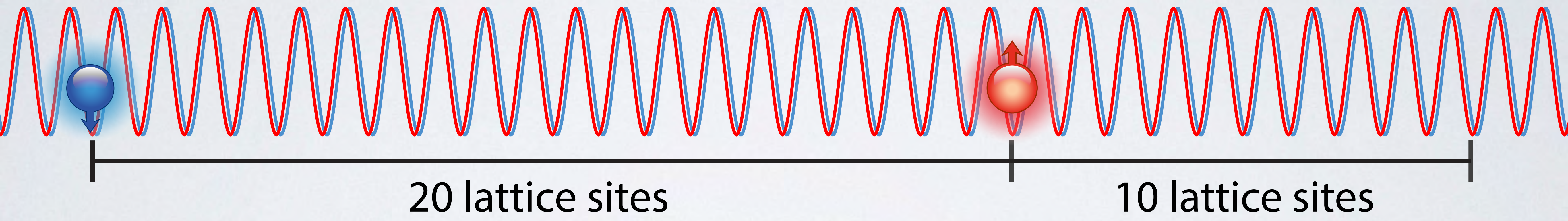

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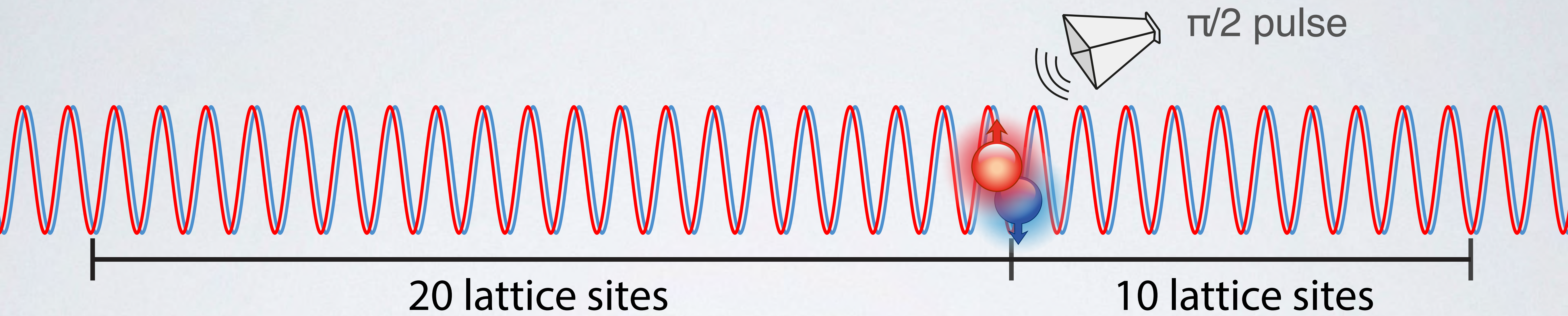

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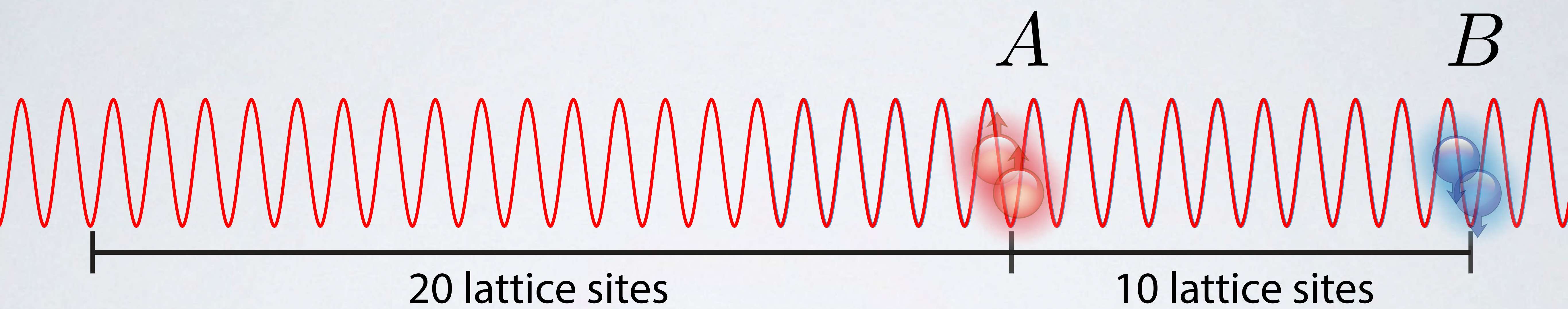

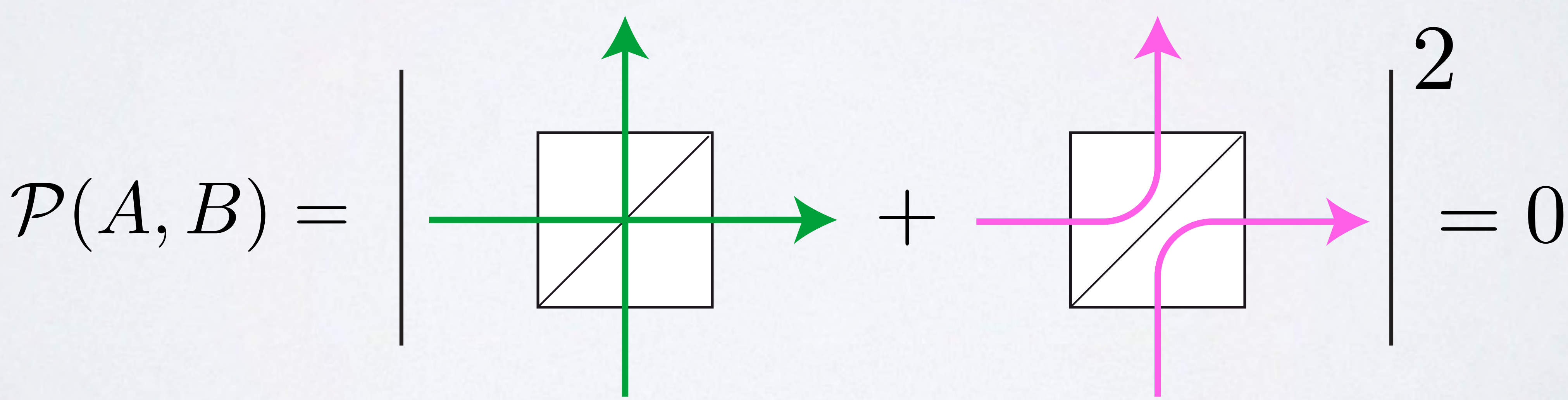

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3D ground state cooling

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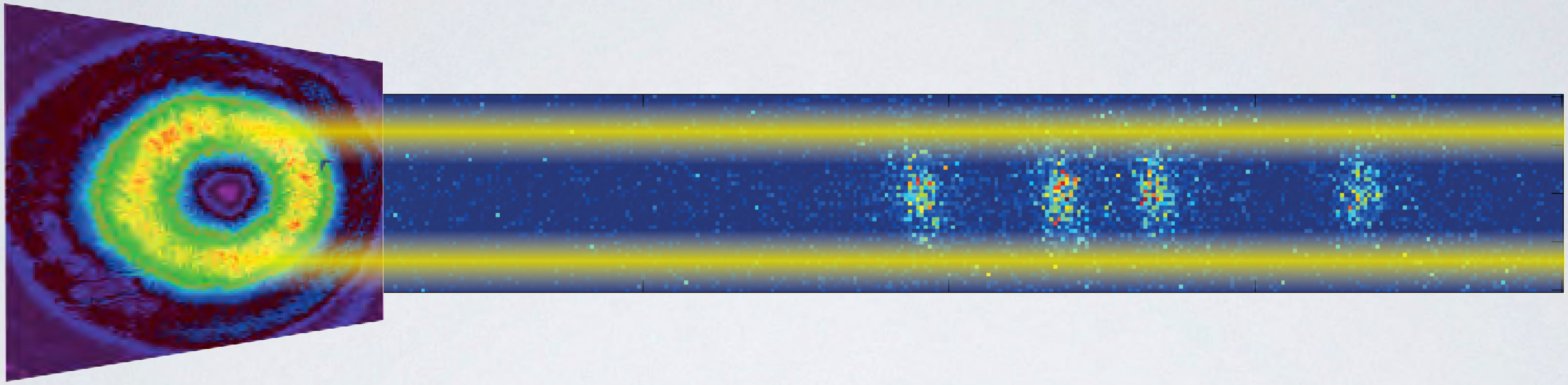

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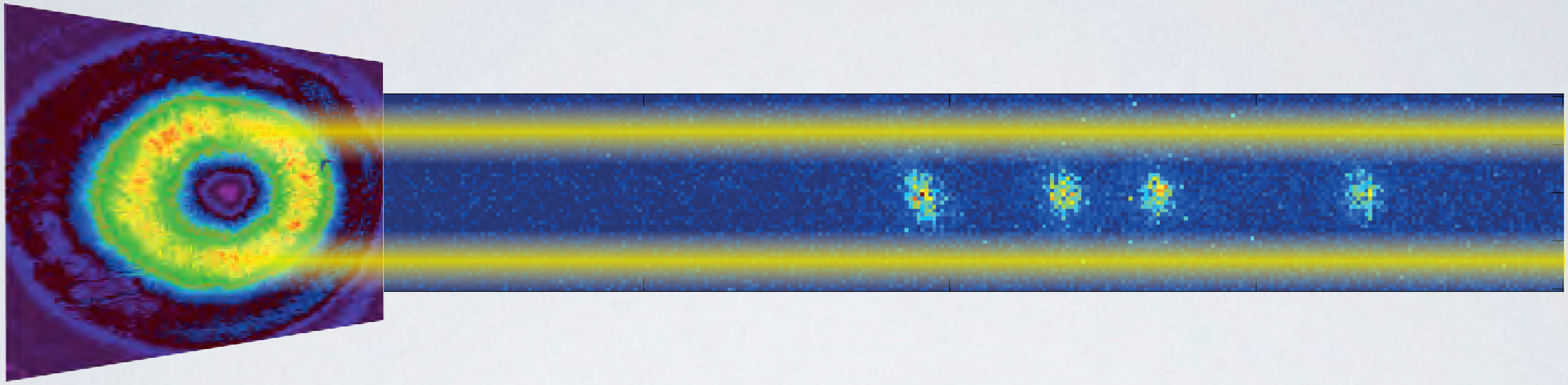

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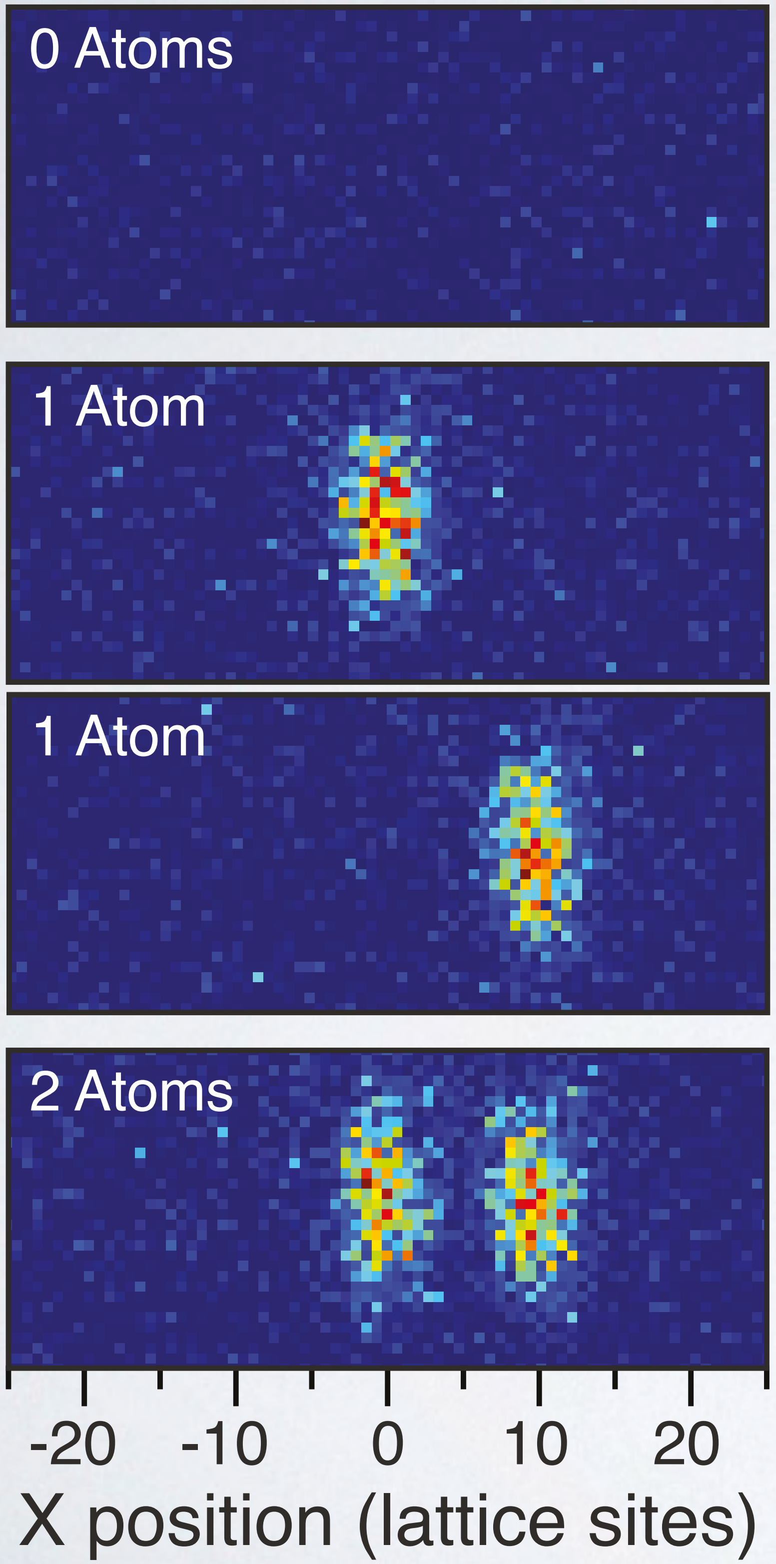

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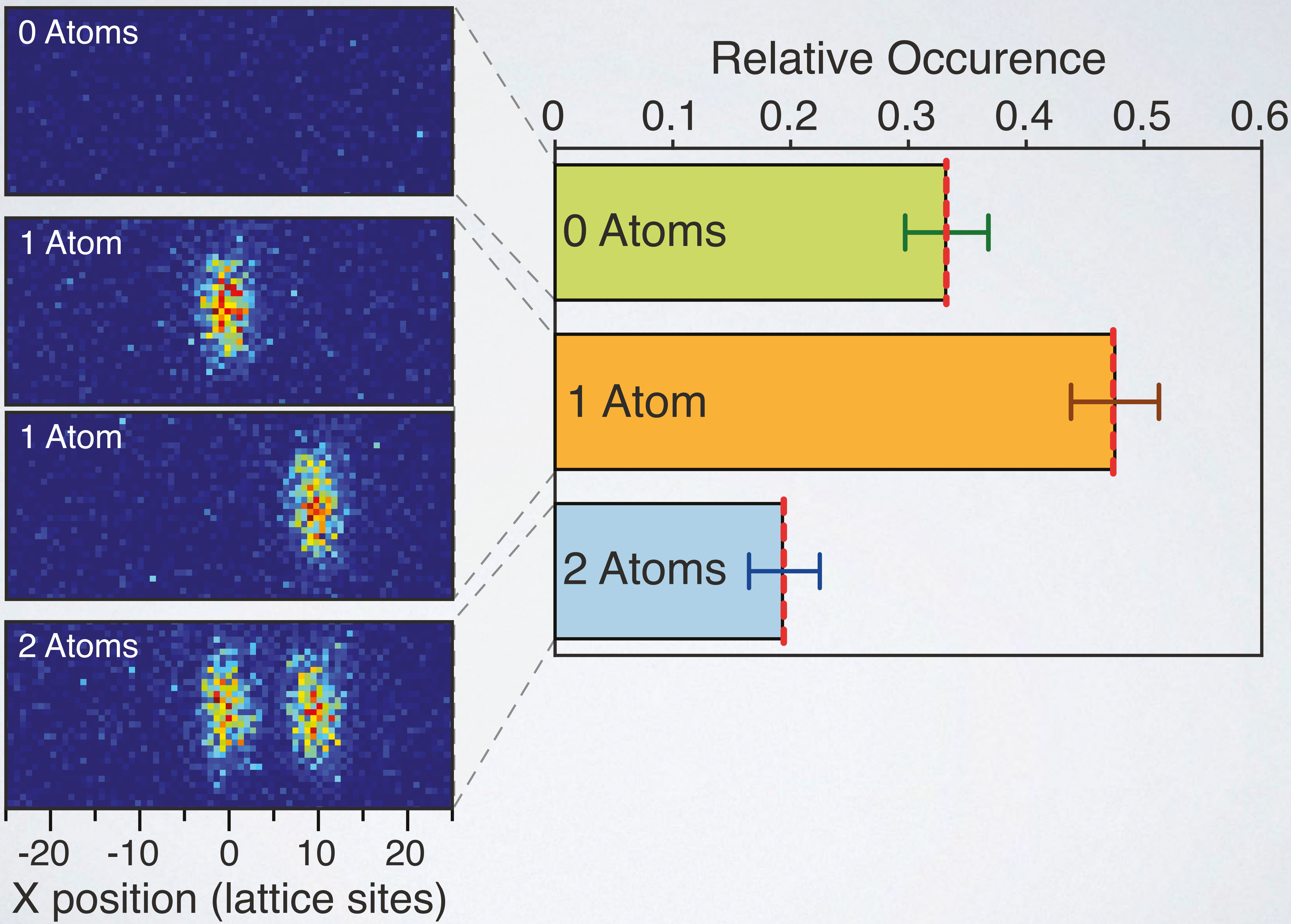

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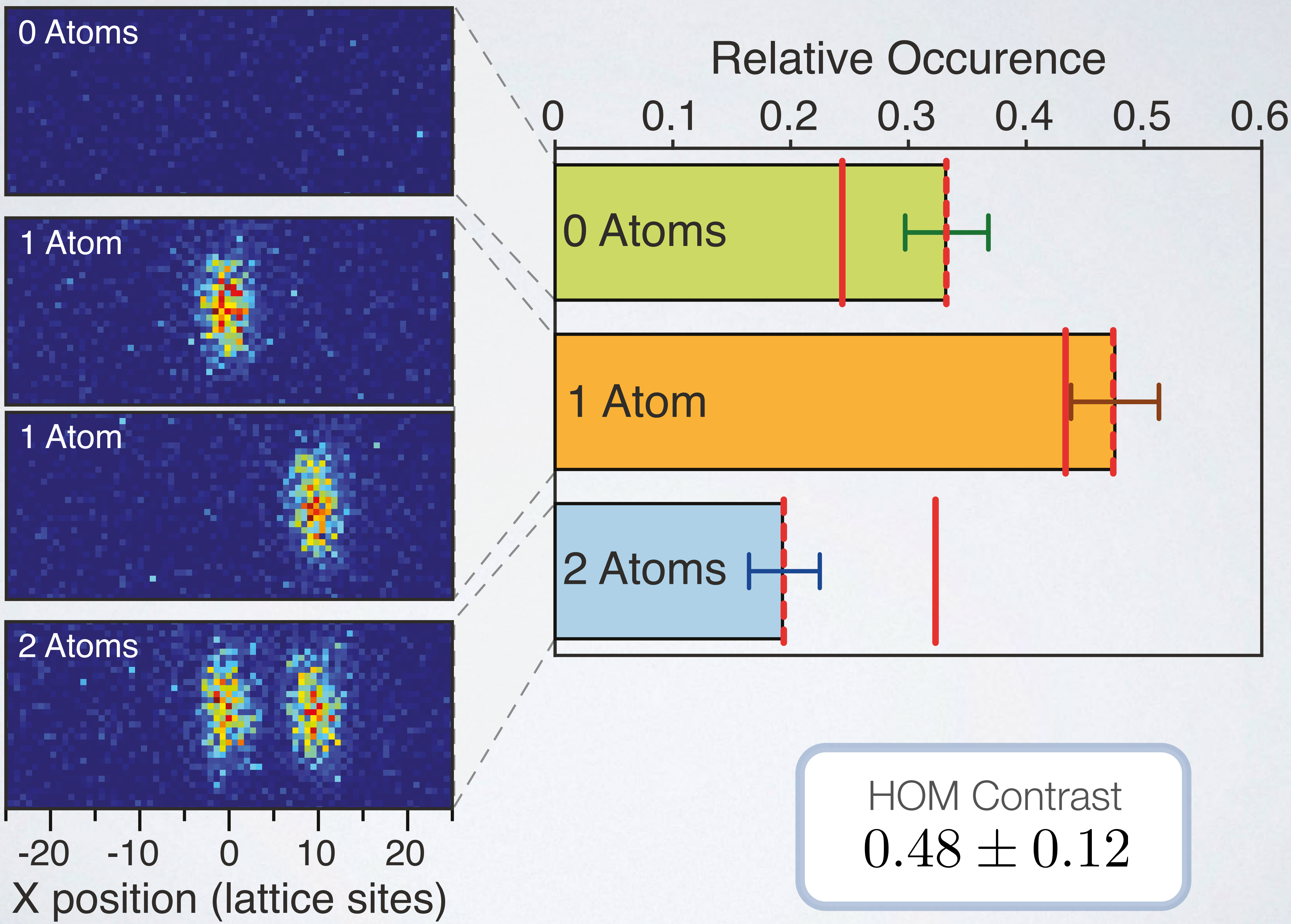

HOM Contrast
0.48 ± 0.12

Revealing quantum statistics with a pair of distant atoms

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There is no need to antisymmetrize if the electrons are far apart and the overlap is negligible. This is quite gratifying. We never have to worry about the question of antisymmetrization with 10 billion electrons, nor is it necessary to take into account the antisymmetrization requirement between an electron in Los Angeles and an electron in Beijing.

J. J. Sakurai, Modern Quantum Mechanics

Physics

C. F. Roos, A. Alberti, D. Meschede, P. Hauke, and H. Häffner, "Revealing Quantum Statistics with a Pair of Distant Atoms," Phys. Rev. Lett. **119**, 160401 (2017).

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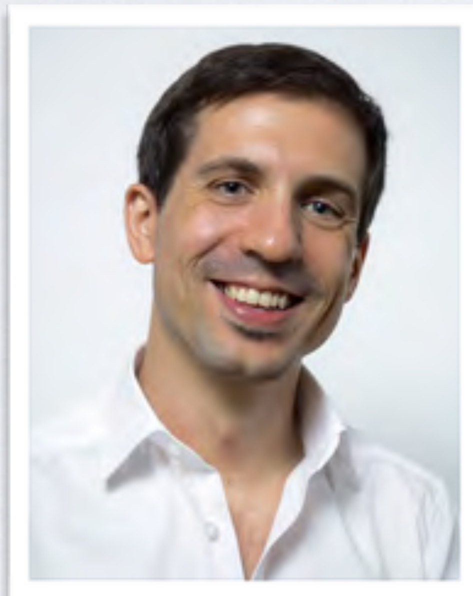
Christian Roos	Andrea Alberti	Dieter Meschede	Philipp Hauke	Hartmut Häffner
				
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$$|\psi\rangle = \hat{a}_L^\dagger \, \hat{a}_R^\dagger \, |0\rangle$$

$$\varphi_{\mathrm{ex}} = \begin{cases} 0 & \text{for Bosons} \\ \pi & \text{for Fermions} \end{cases}$$

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$$|\psi\rangle = \hat{a}^\dagger_R \, \hat{a}^\dagger_L \, |0\rangle = e^{i\varphi_{\mathrm{ex}}} \hat{a}^\dagger_L \hat{a}^\dagger_R |0\rangle$$

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$$|\psi\rangle = \frac{\hat{a}_R^\dagger \hat{a}_L^\dagger + \hat{b}_R^\dagger \hat{b}_L^\dagger}{\sqrt{2}} |0\rangle$$

$\varphi_{\mathrm{ex}} = \begin{cases} 0 & \text{for Bosons} \\ \pi & \text{for Fermions} \end{cases}$

Revealing quantum statistics with a pair of distant atoms

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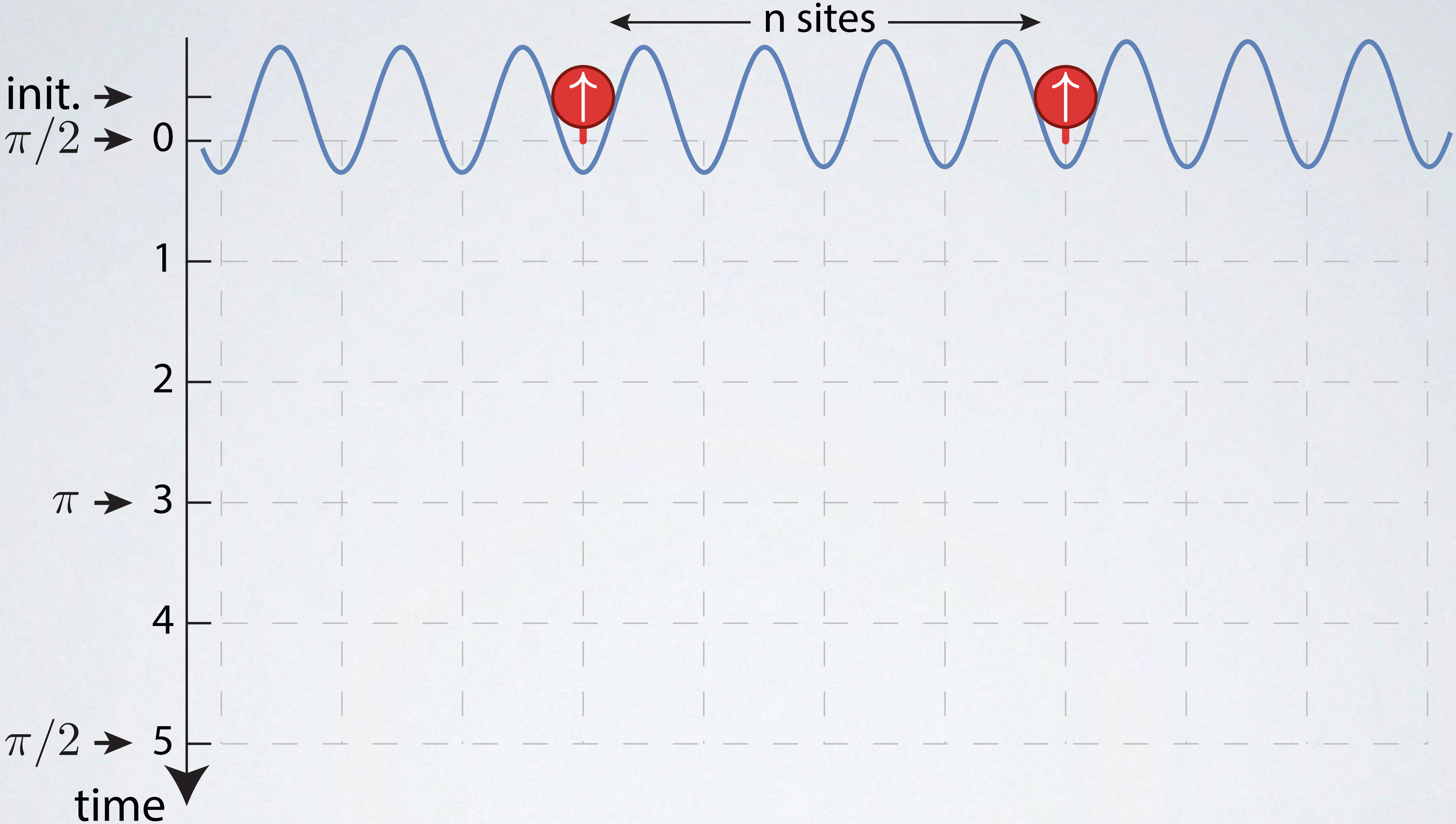

Physics

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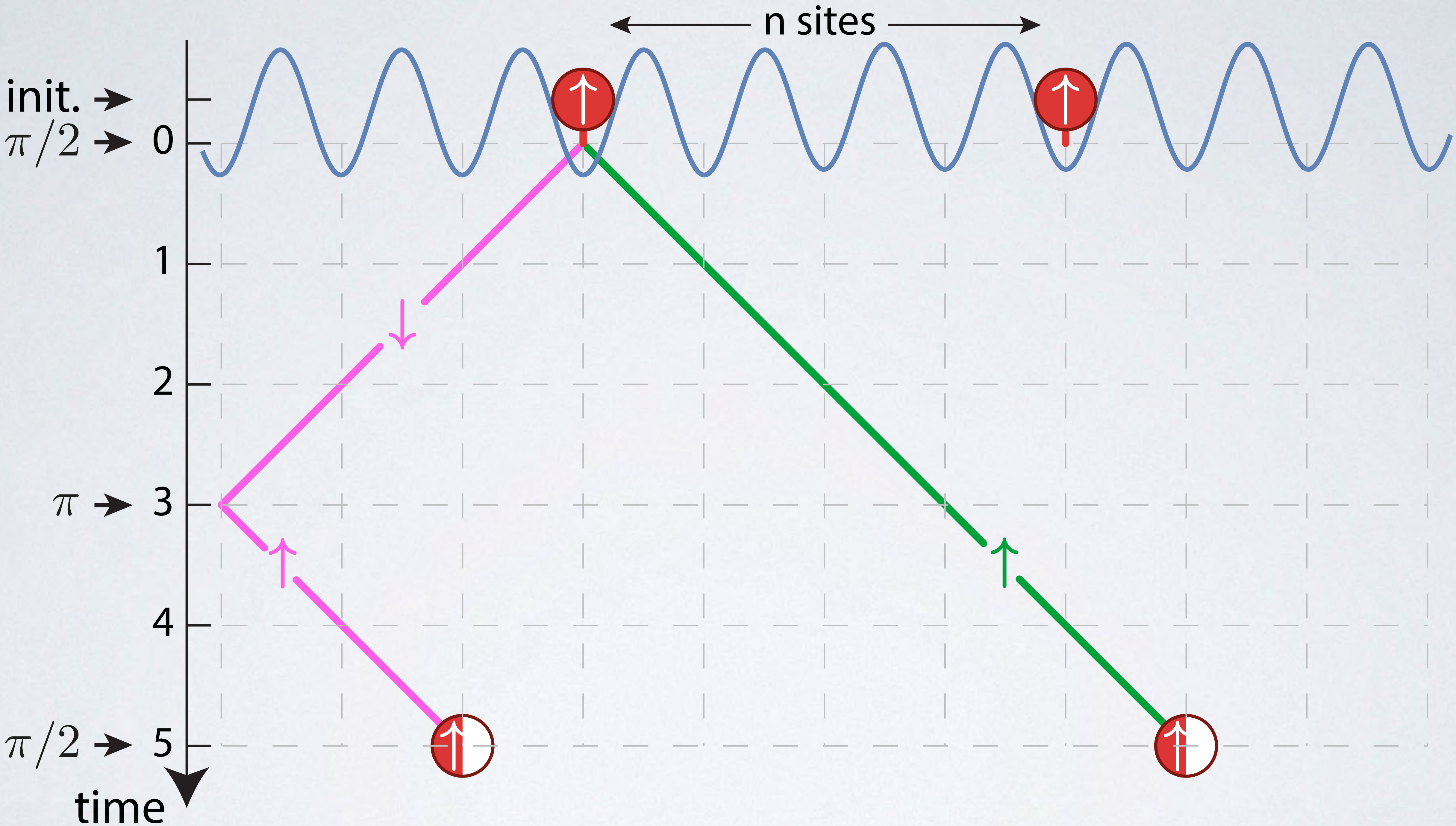

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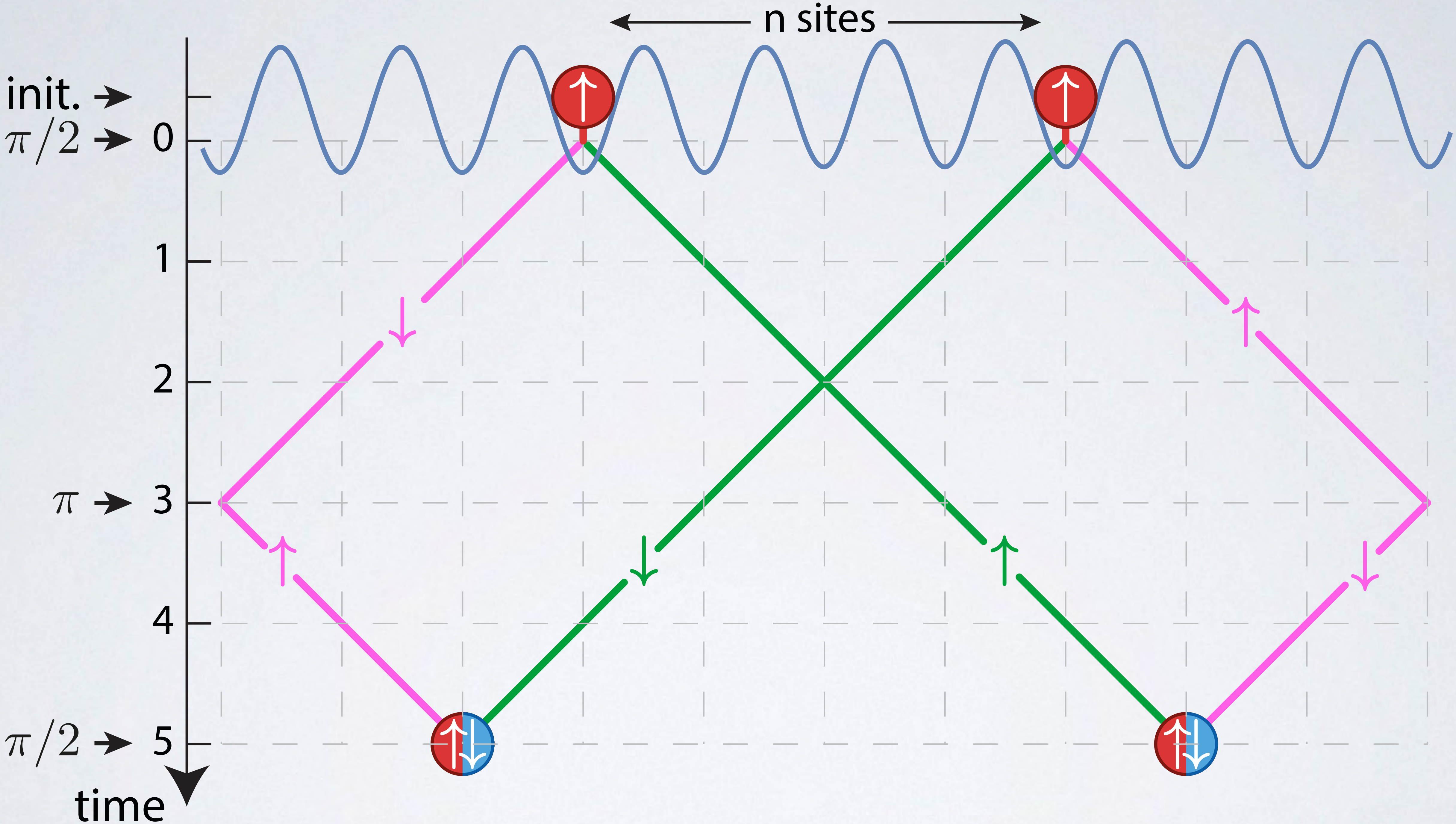

Physics C. F. Roos, A. Alberti, D. Meschede, P. Hauke, and H. Häffner, “Revealing Quantum Statistics with a Pair of Distant Atoms,” Phys. Rev. Lett. **119**, 160401 (2017).

Revealing quantum statistics with a pair of distant atoms

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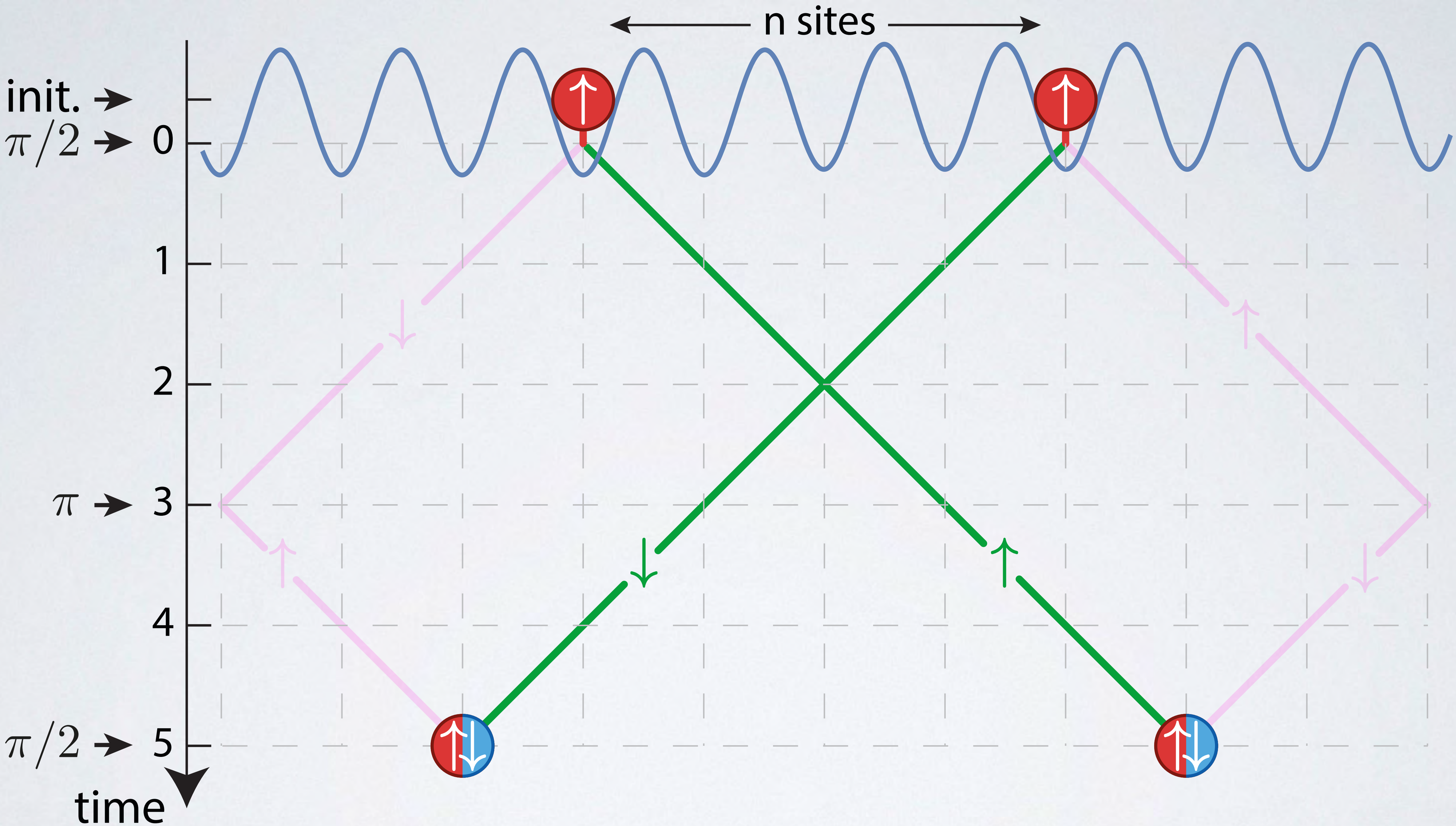

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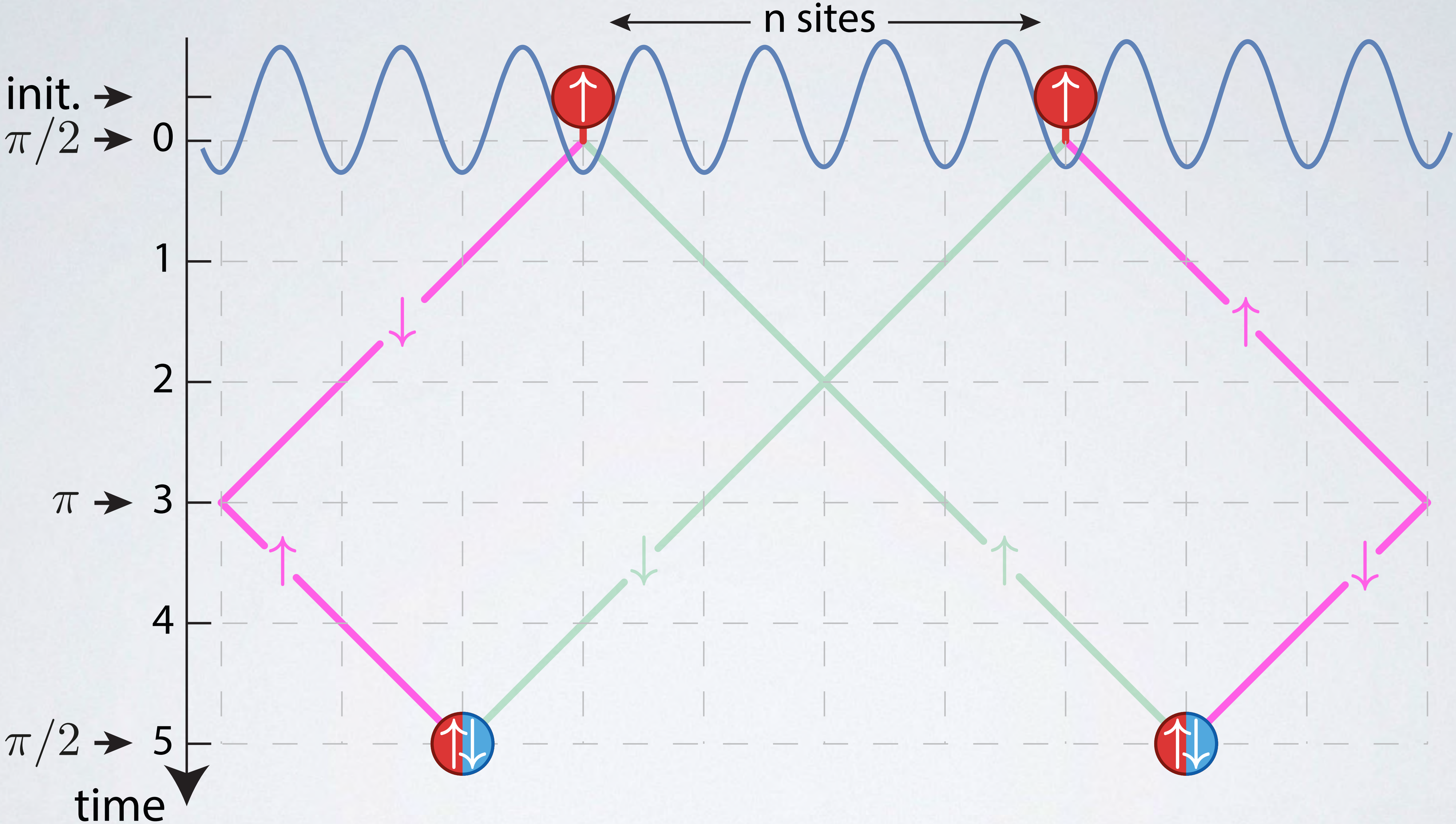

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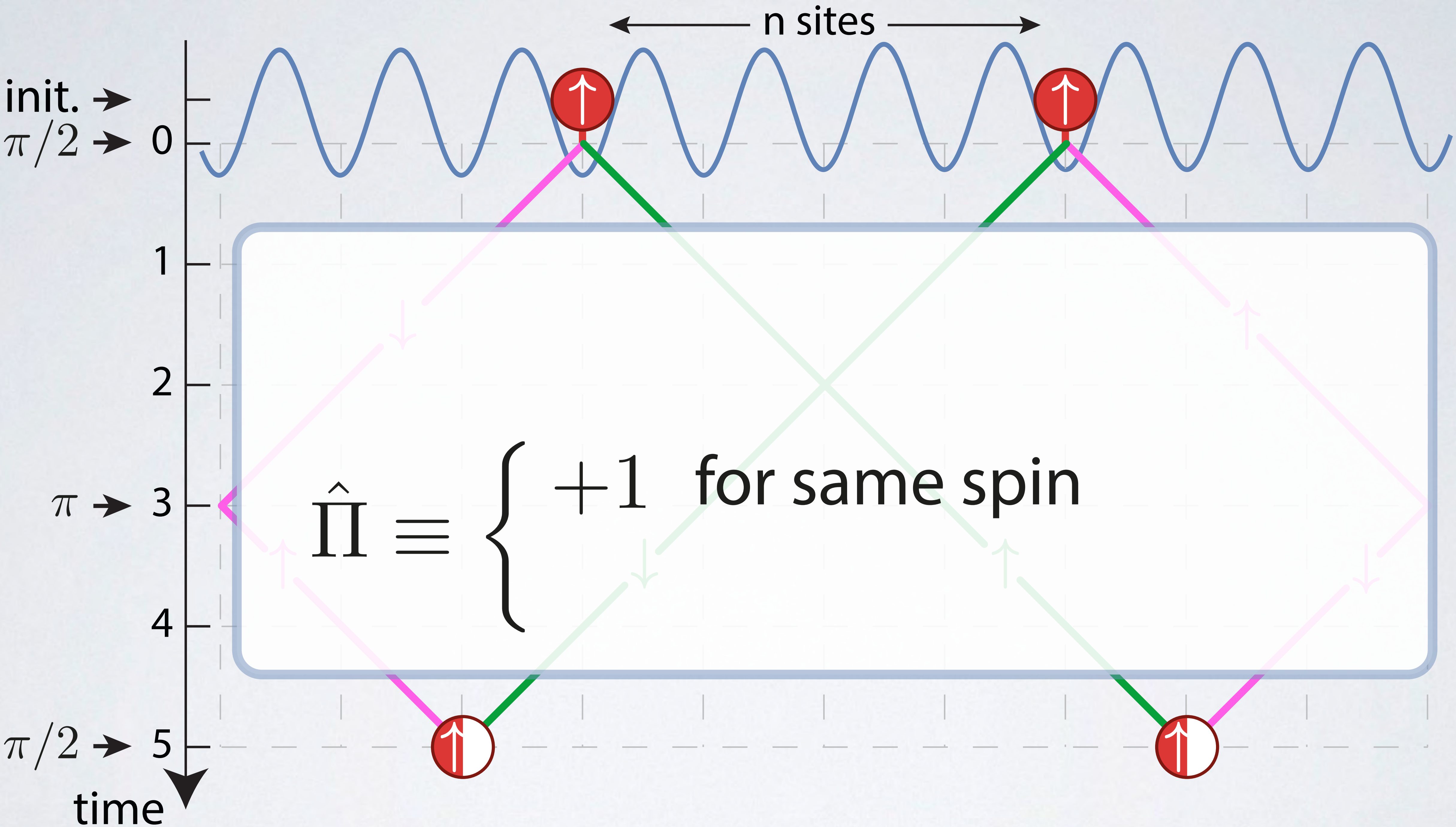

$$\hat{\Pi} \equiv \begin{cases} +1 & \text{for same spin} \\ & \end{cases}$$

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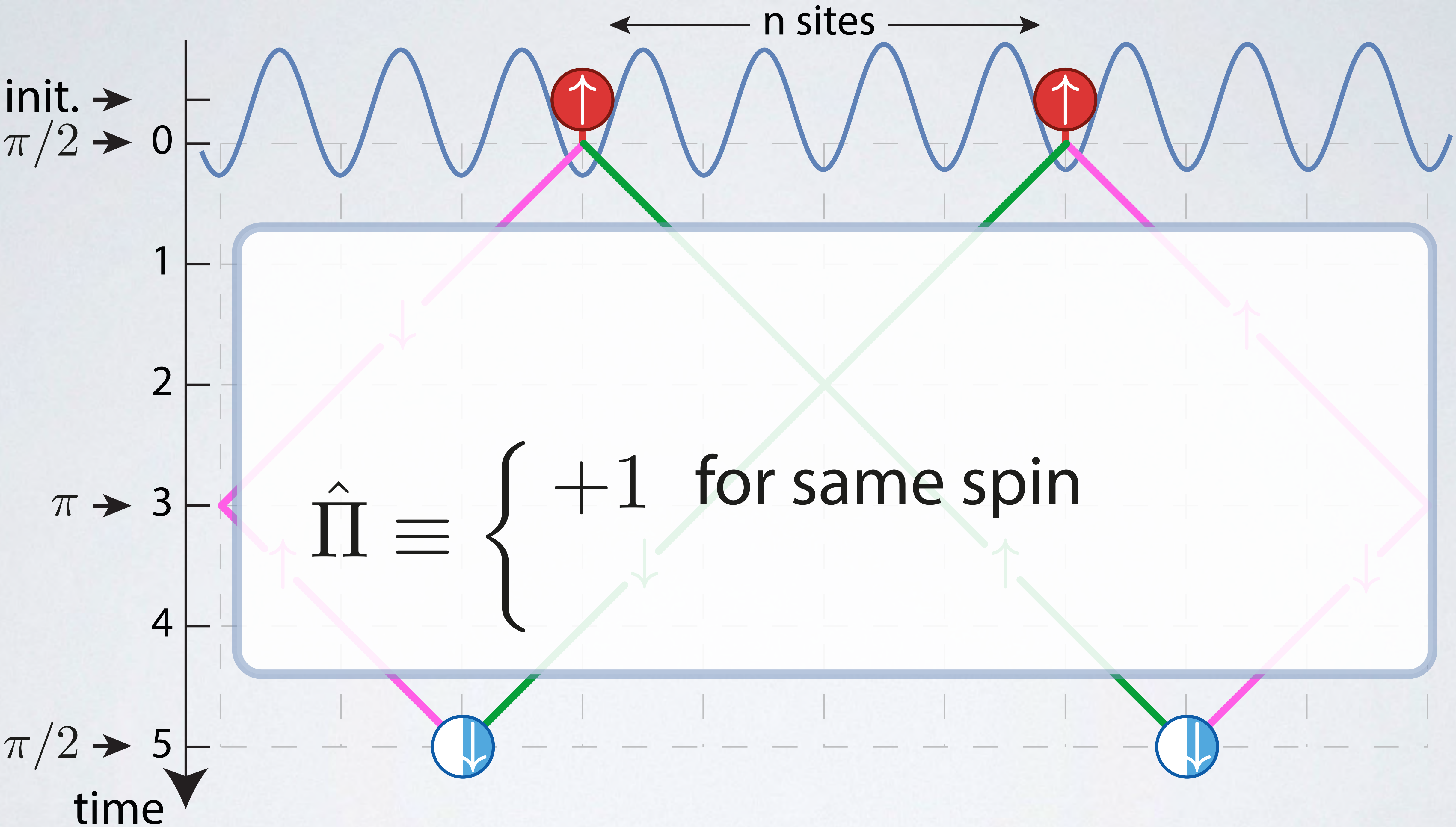

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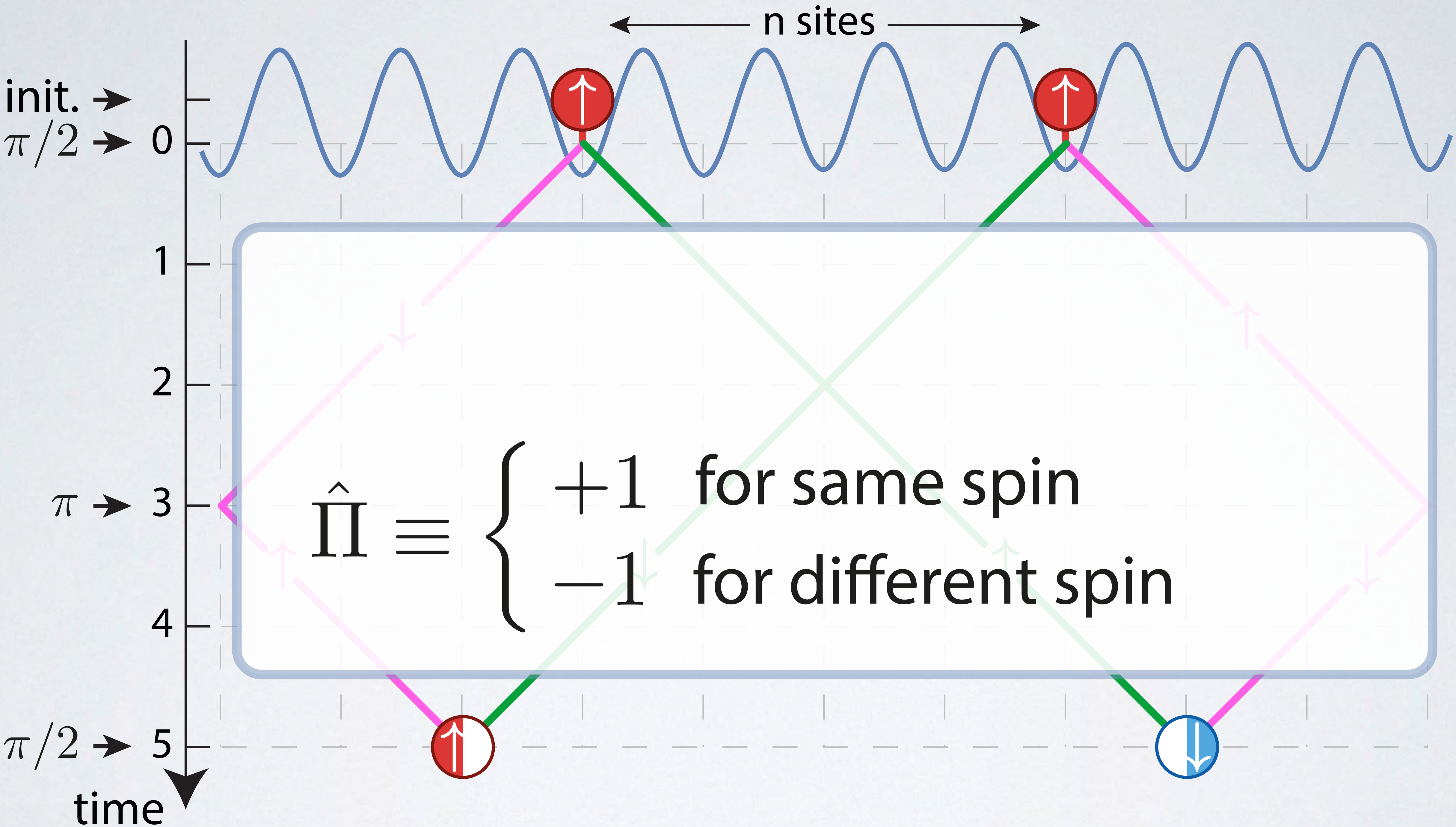

$$\hat{\Pi} \equiv \begin{cases} +1 & \text{for same spin} \\ -1 & \text{for different spin} \end{cases}$$

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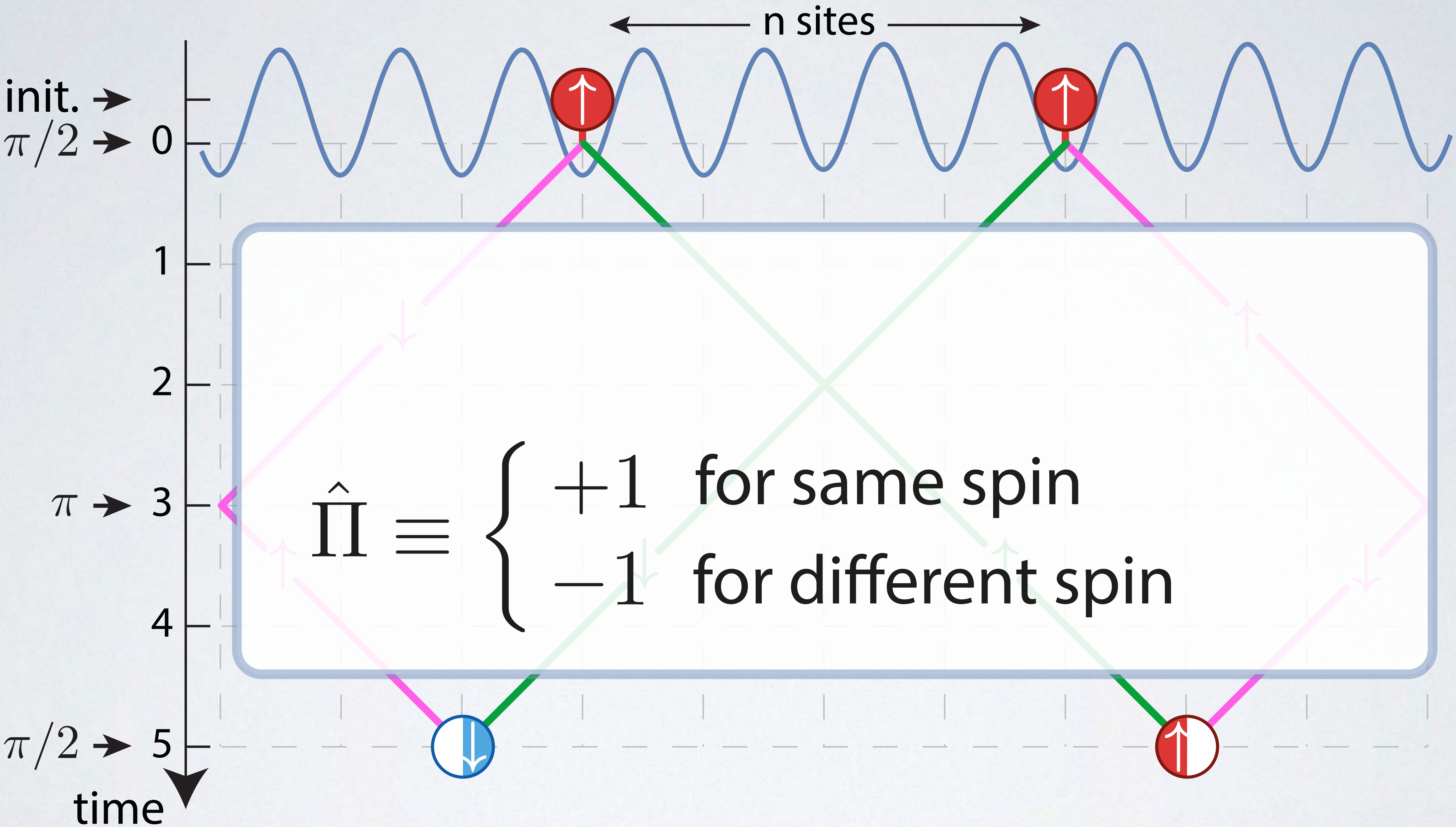

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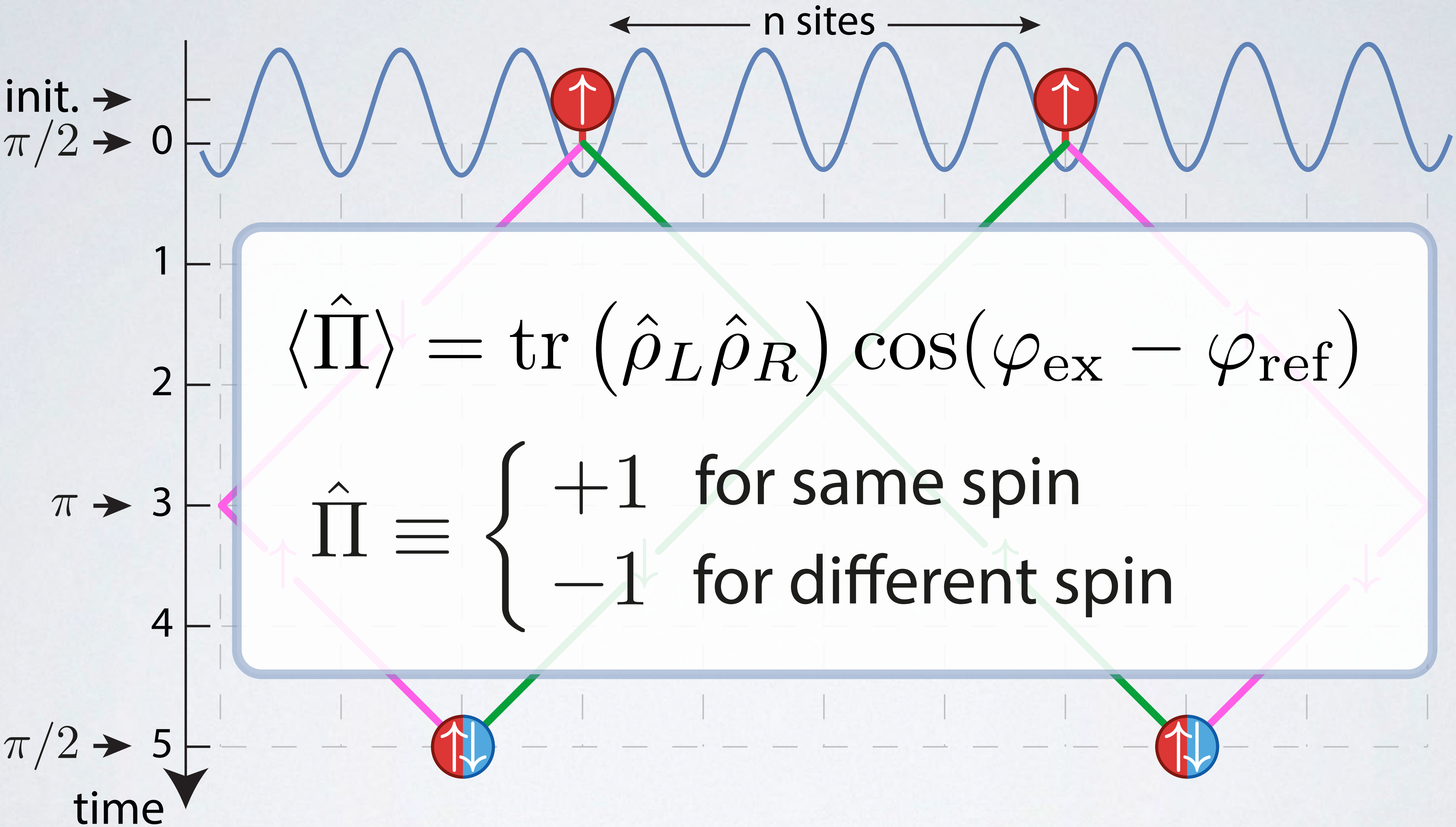

$$\langle \hat{\Pi} \rangle = \mathrm{tr}\left(\hat{\rho}_L \hat{\rho}_R\right) \cos(\varphi_{\mathrm{ex}} - \varphi_{\mathrm{ref}})$$

$$\hat{\Pi} \equiv \begin{cases} +1 & \text{for same spin} \\ -1 & \text{for different spin} \end{cases}$$

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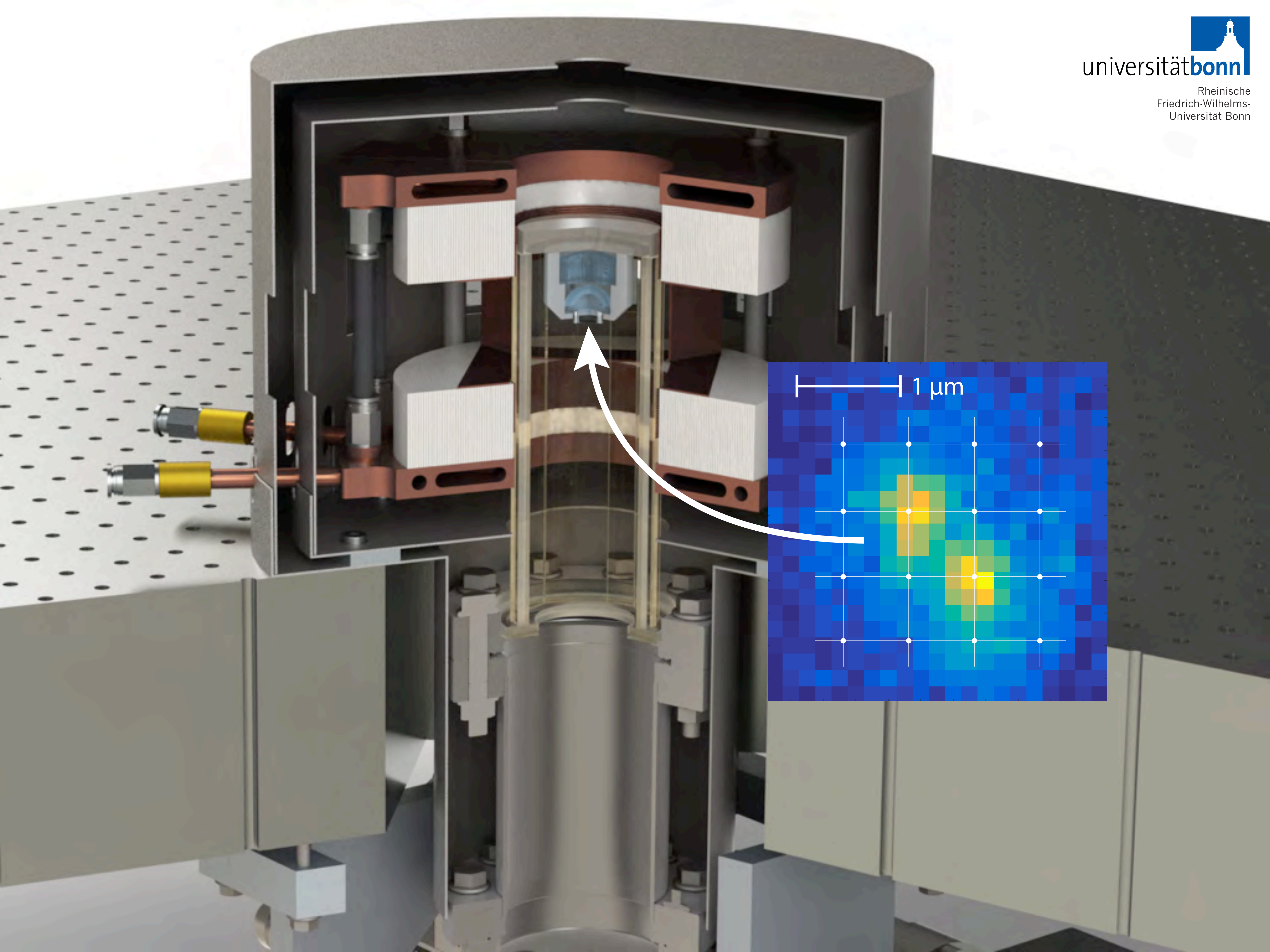

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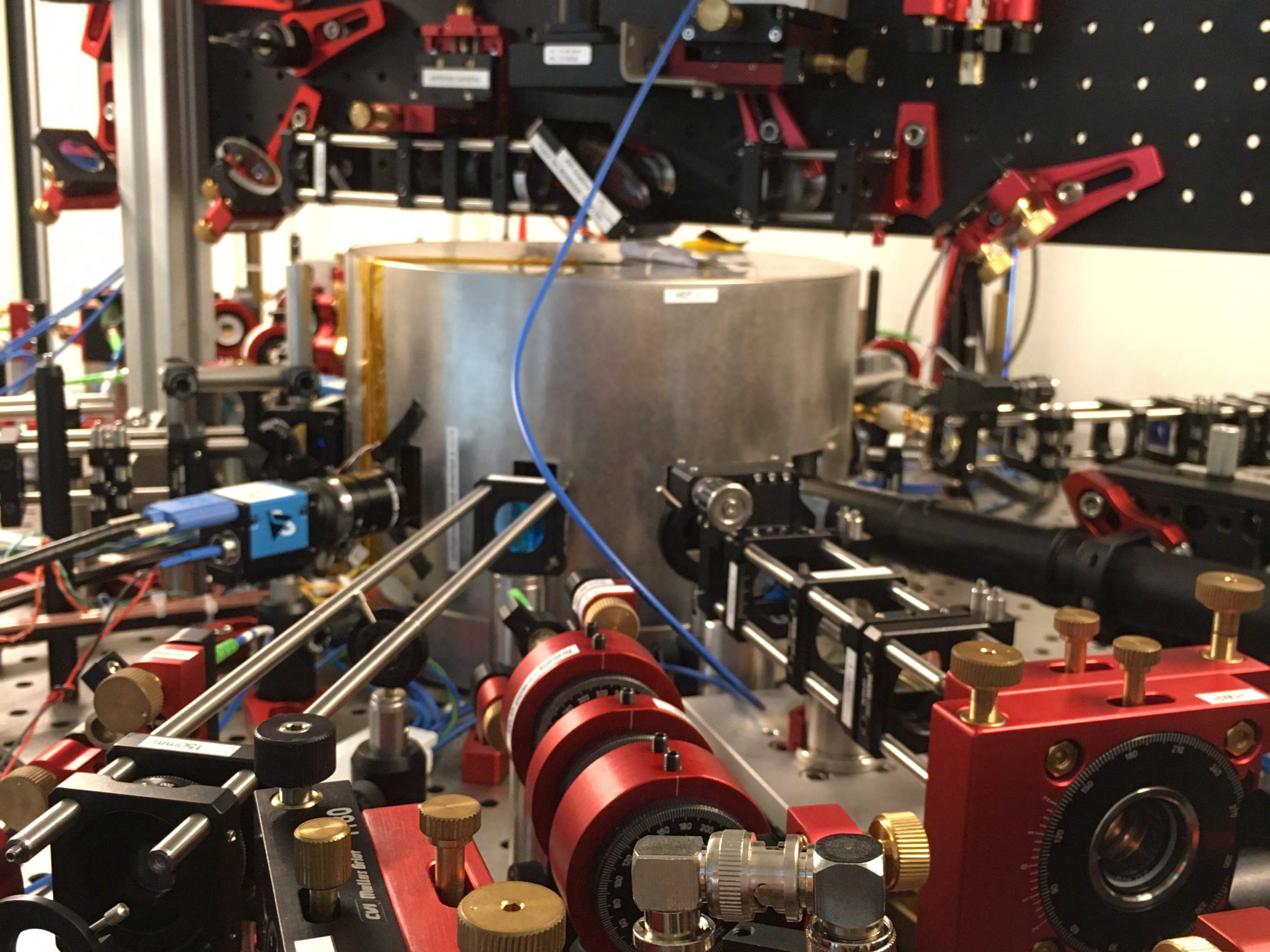
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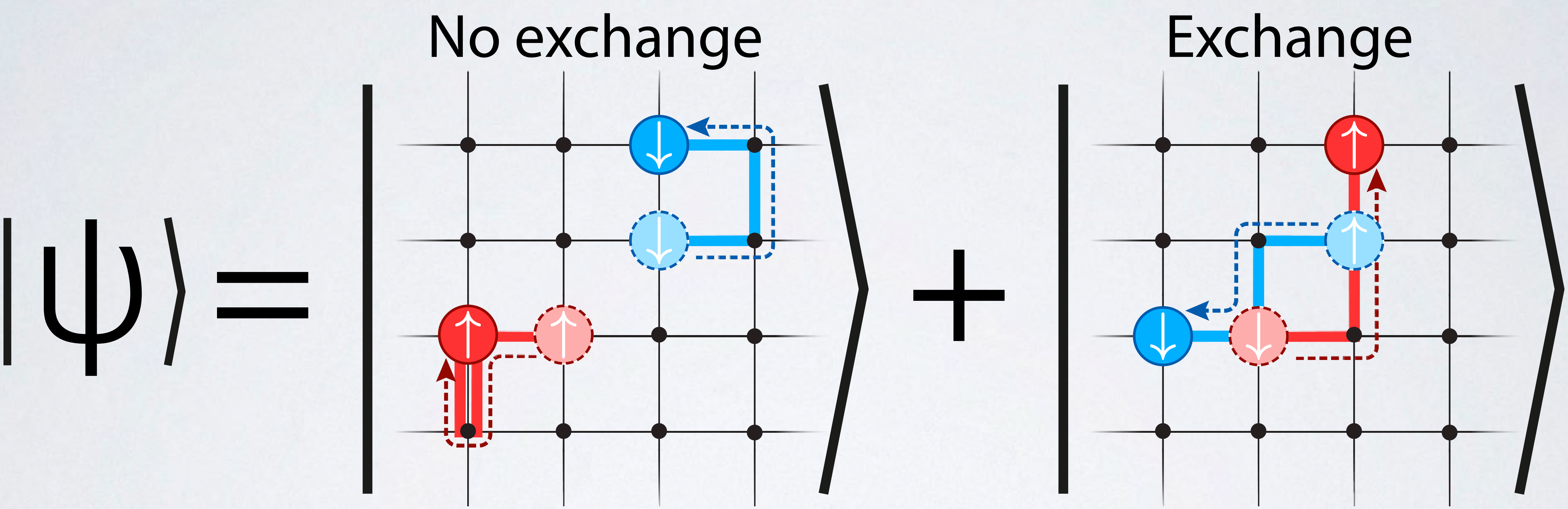

Conclusions

What it is not:

- It is not a test of symmetrization postulate — For that, we would need more than two particles
- It is not a test of spin-statistics connection — A small admixture of opposite statistics would only lead to a reduction of the fringe contrast.

Conclusions

What it is not:

- It is not a test of symmetrization postulate — For that, we would need more than two particles
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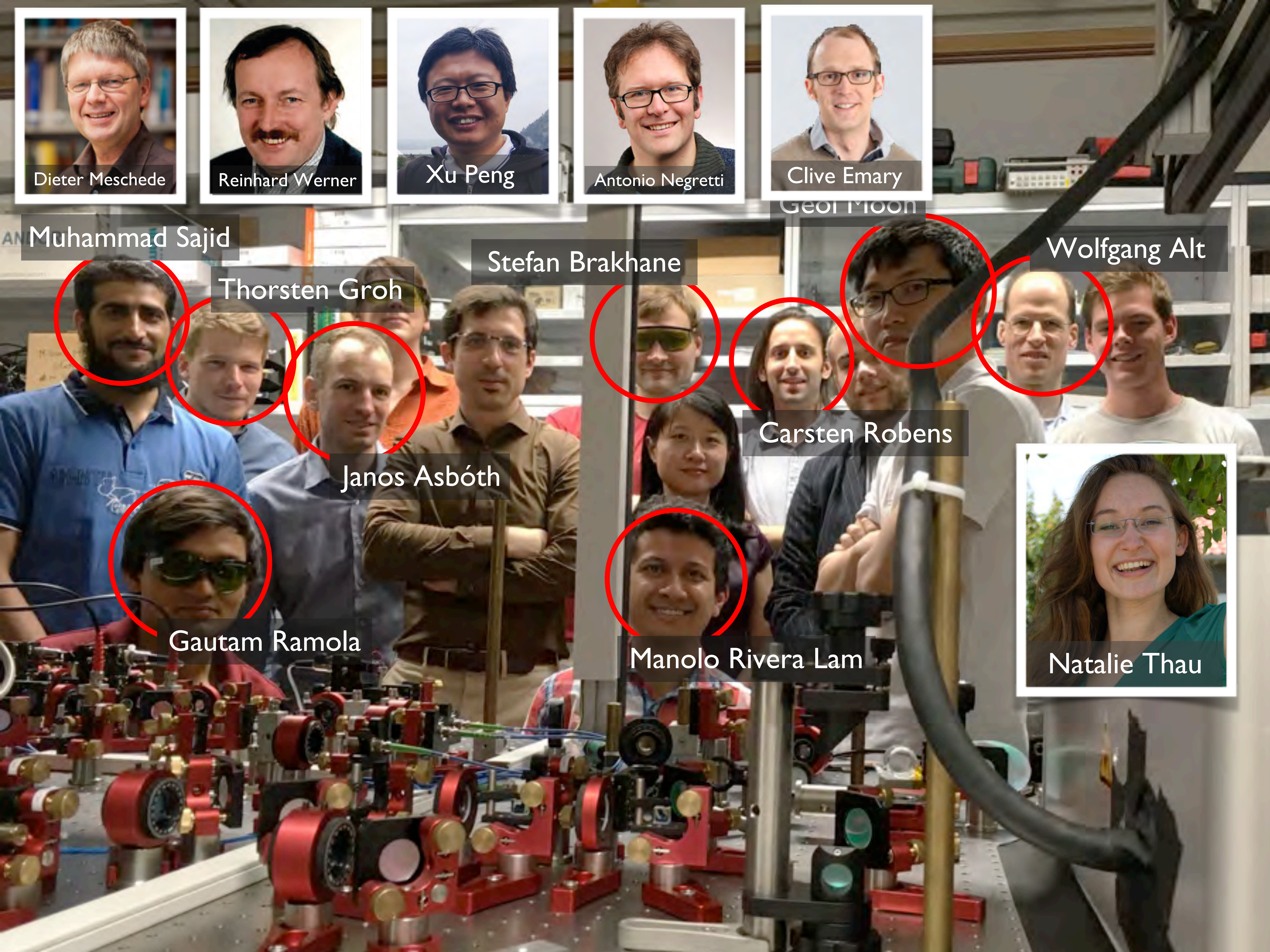
What it is:

- It sets out to directly measure the exchange phase by an interferometric scheme — never attempted
- It shows that we can tell whether atoms are fermions or bosons even if they never cross nor interact
- It is a resource for quantum technology — entanglement generation


Dieter Meschede
Reinhard Werner
Xu Peng
Antonio Negretti
Clive Emary
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