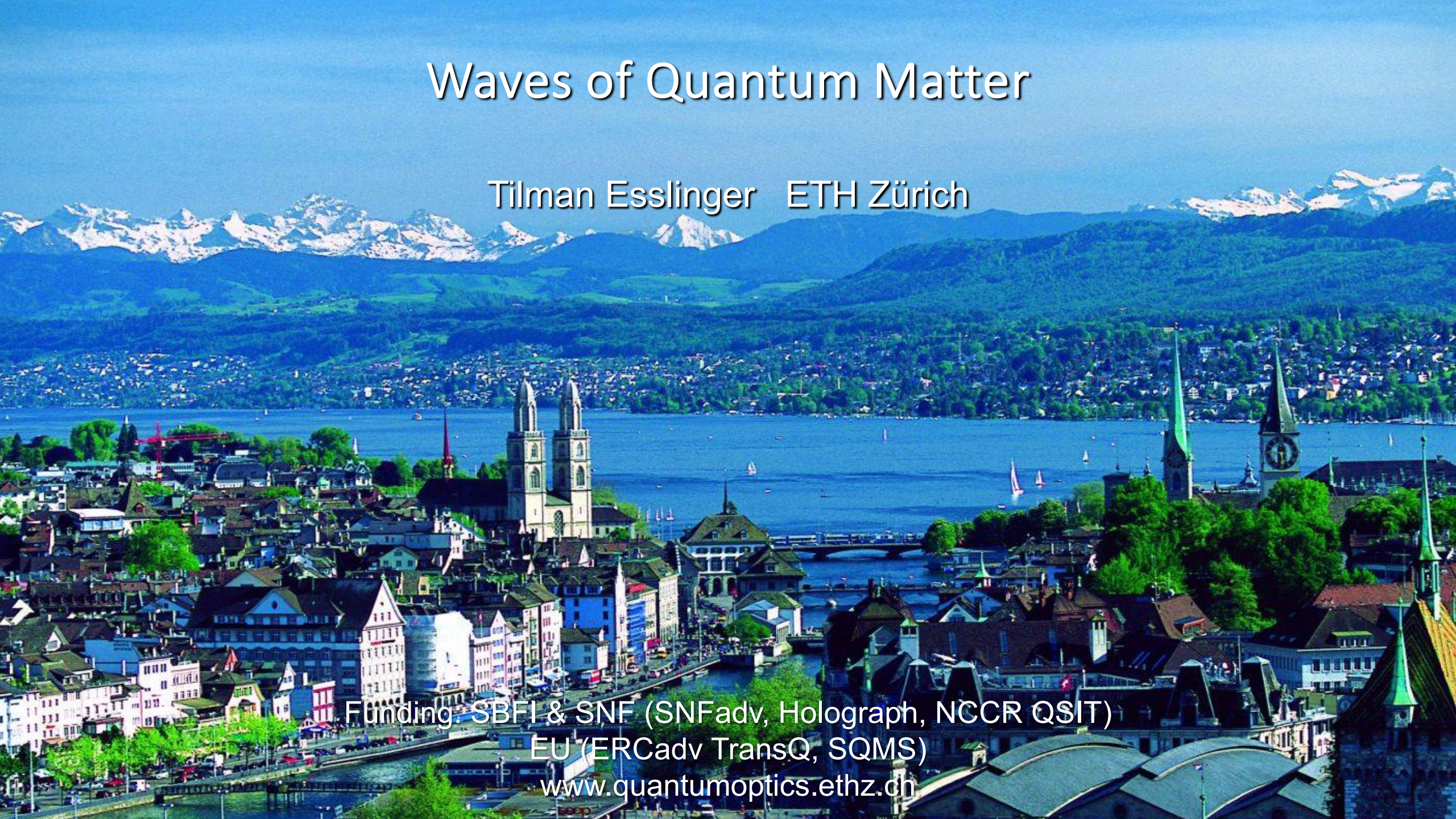
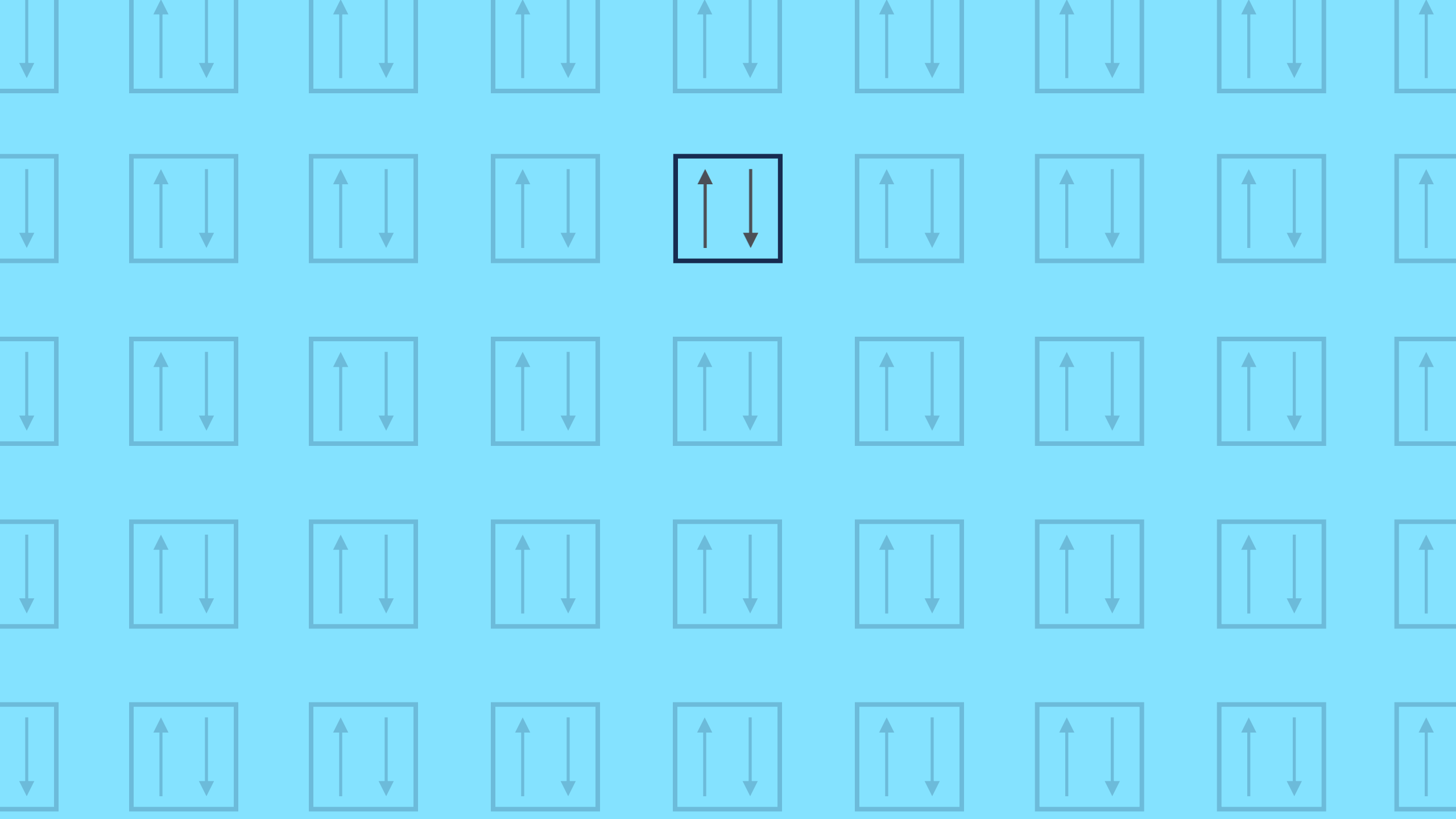
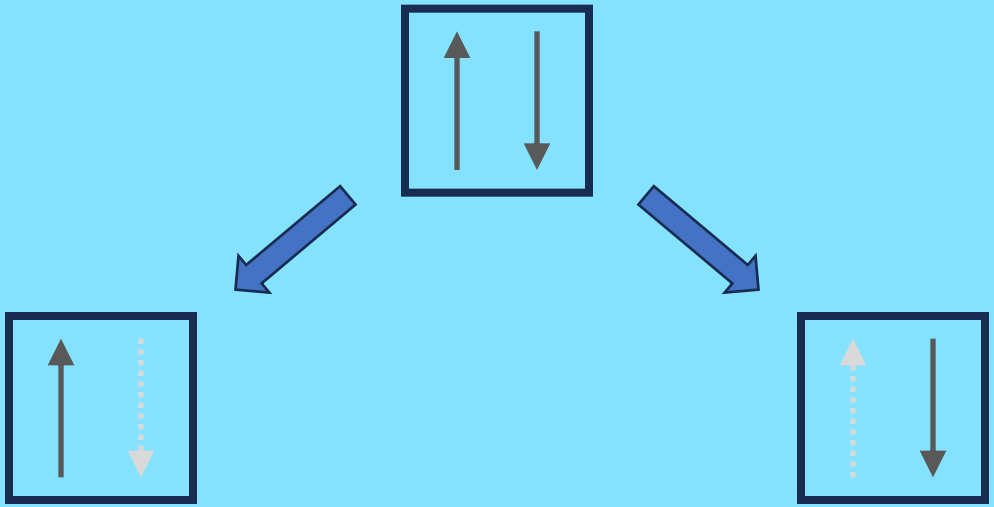
Waves of Quantum Matter

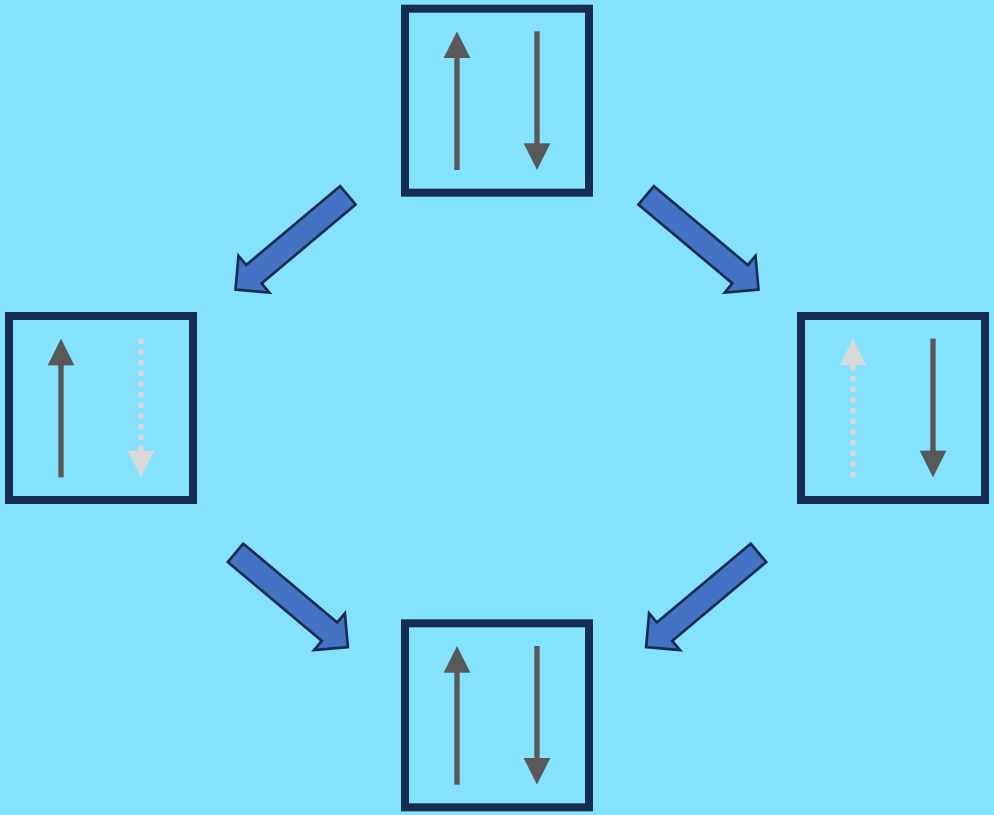
Tilman Esslinger ETH Zürich

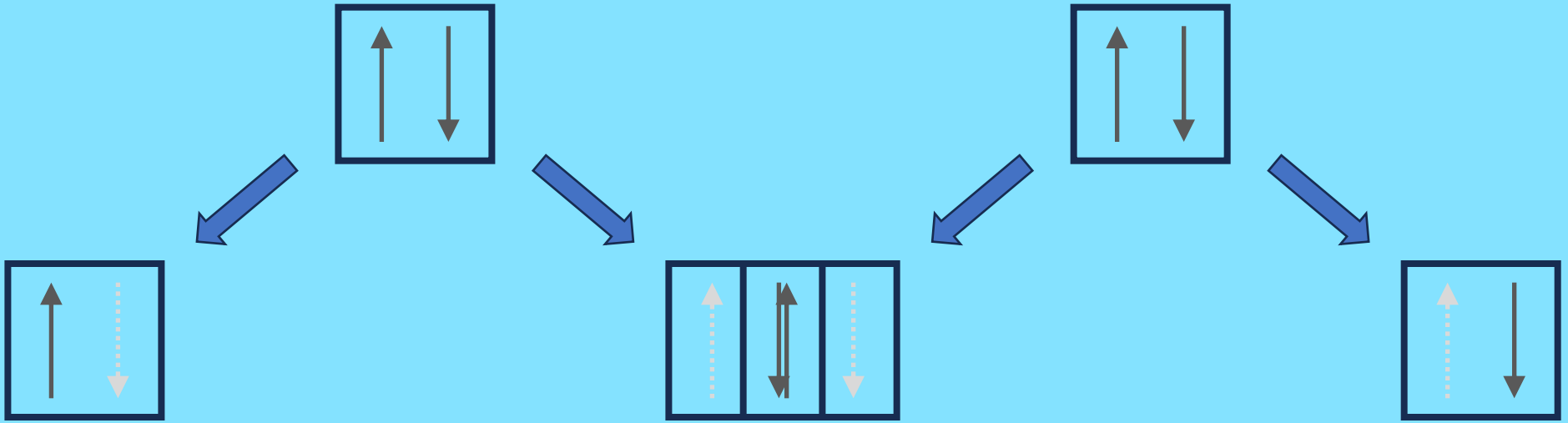


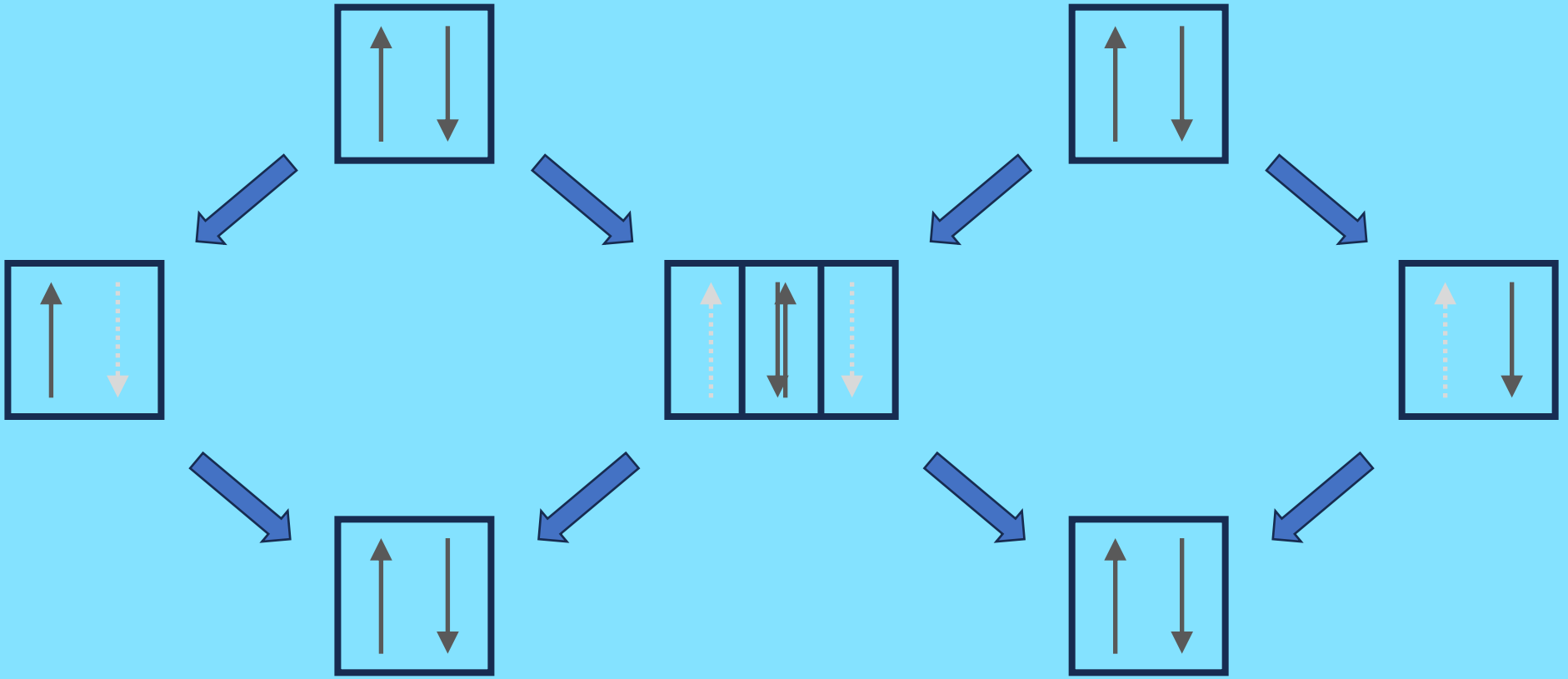
Funding: SBFI & SNF (SNFadv, Holograph, NCCR QSIT)
EU (ERCadv TransQ, SQMS)
www.quantumoptics.ethz.ch



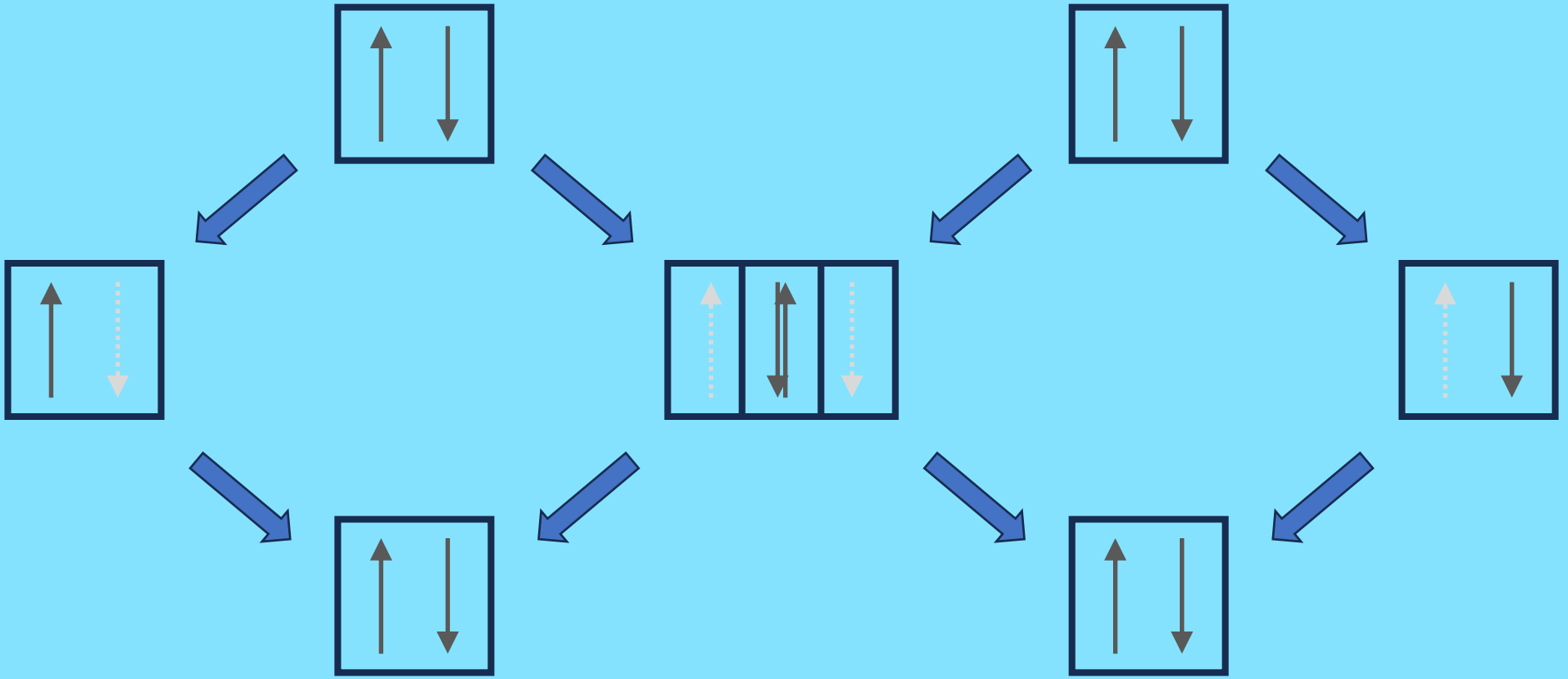


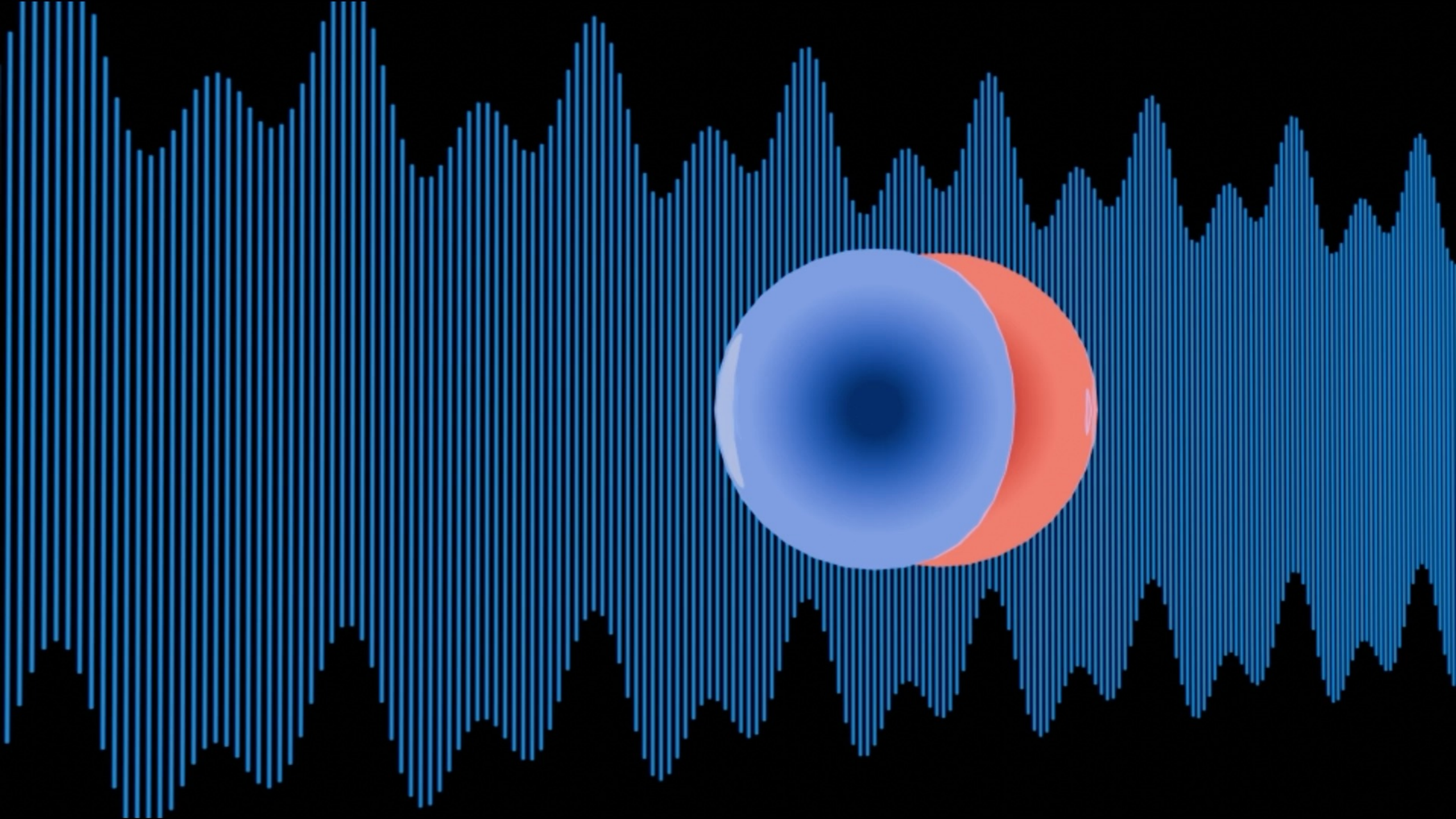






Atoms instead of Electrons



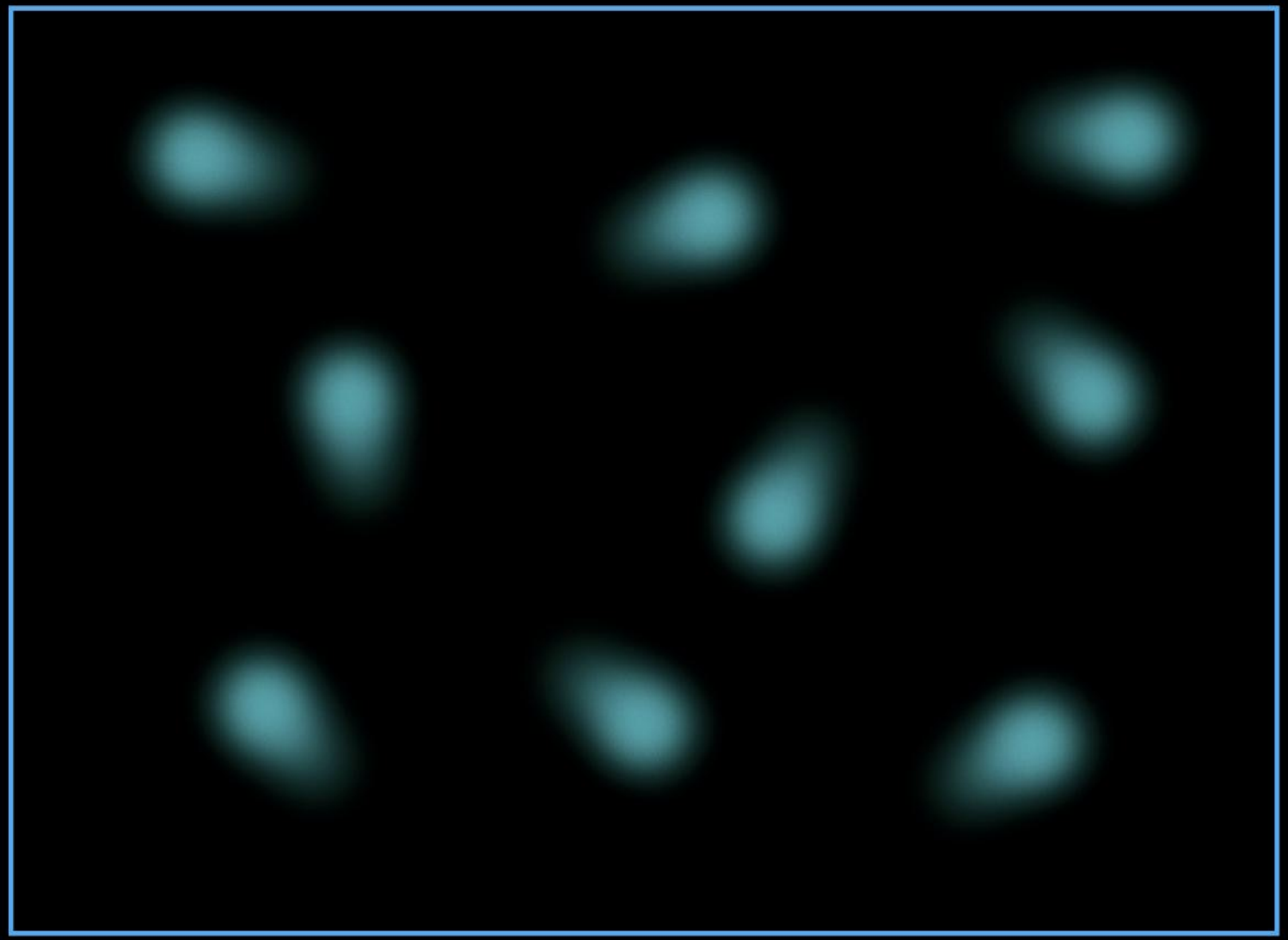


Louis de Broglie

Wikipedia

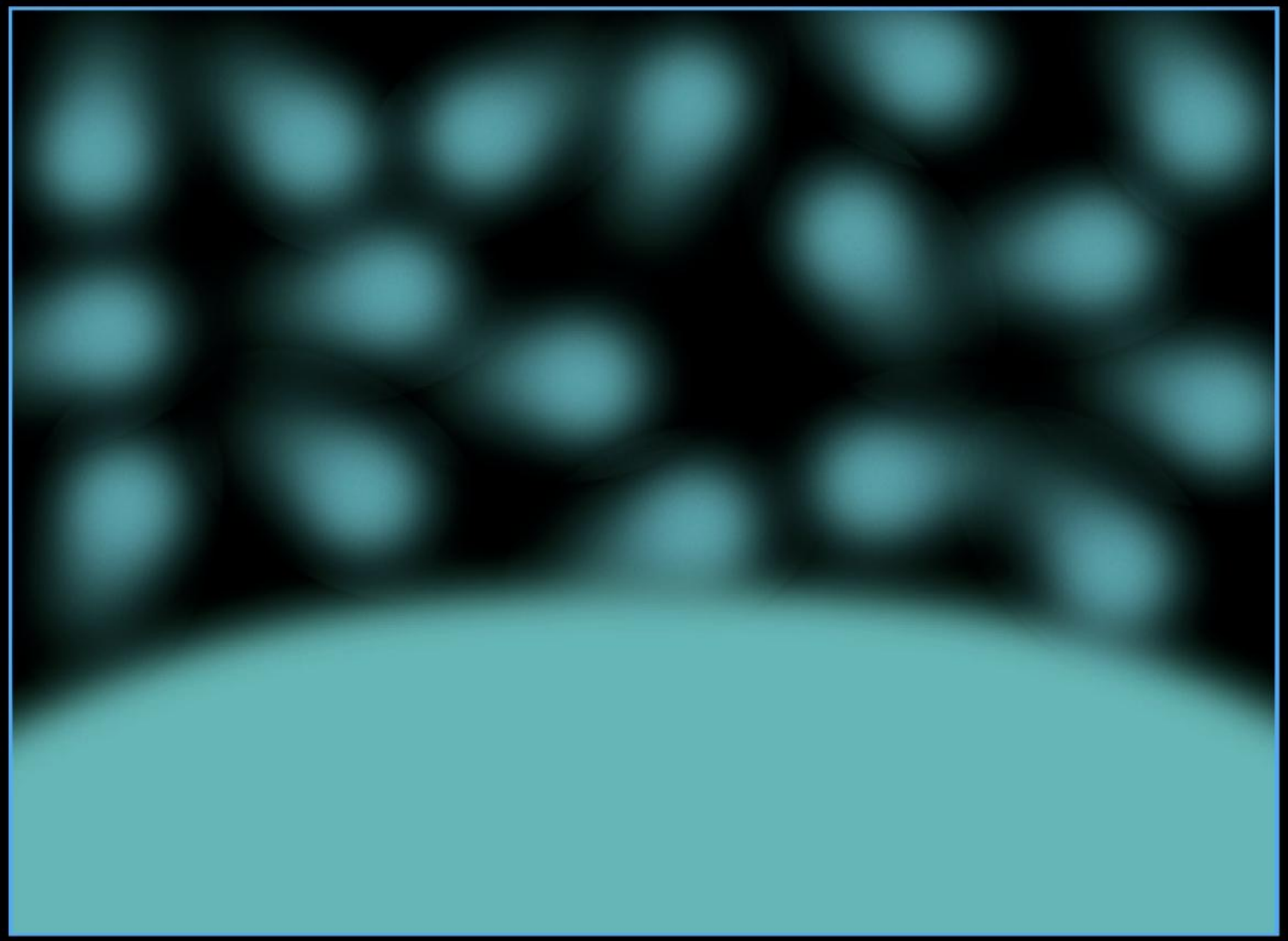
An ultracold gas

$T > T_c$ $\lambda_{db}=h/mv \propto T^{-1/2}$



Condensation

$T < T_c$ $\lambda_{db} = d$

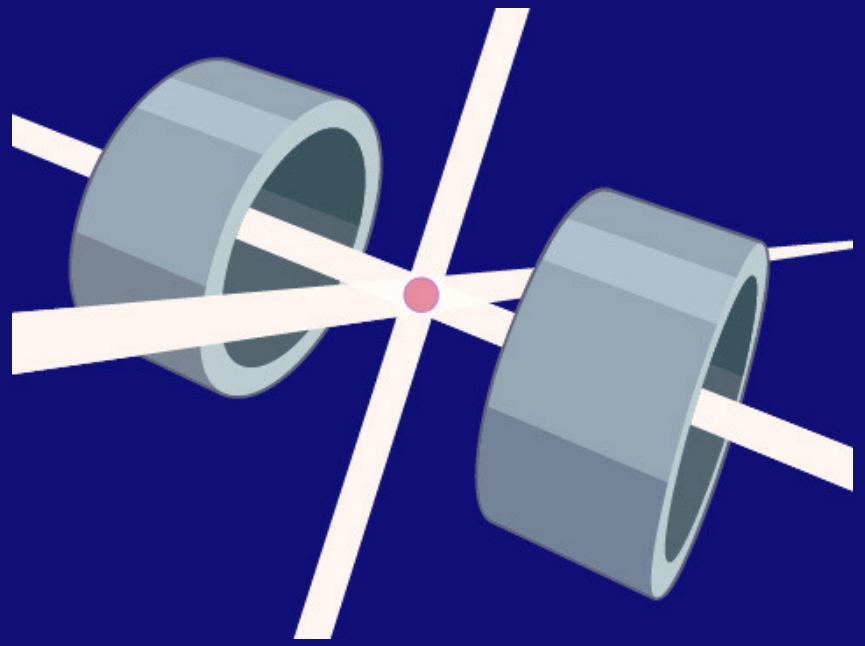


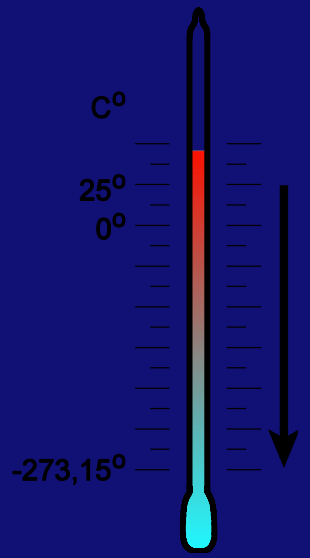
Pure condensate

$T \ll T_c$

Super de Broglie Wave

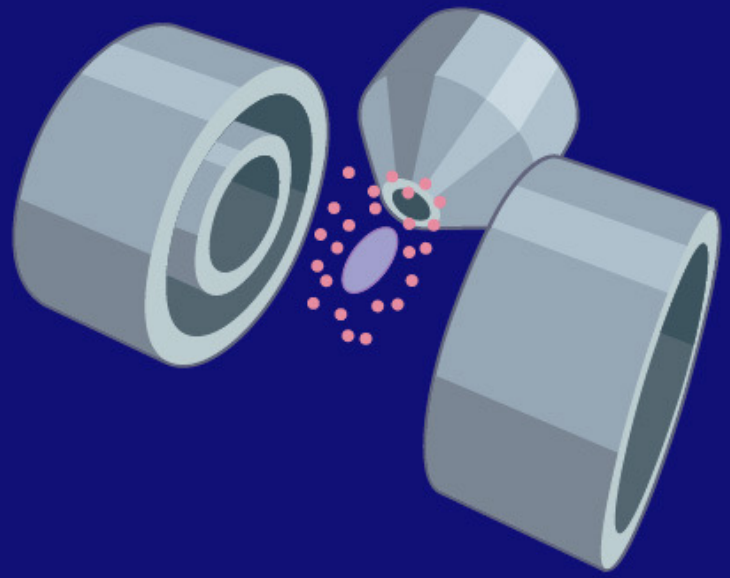
Laser Cooling

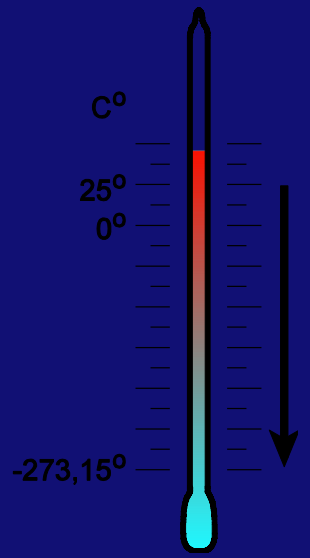




0.1 mK

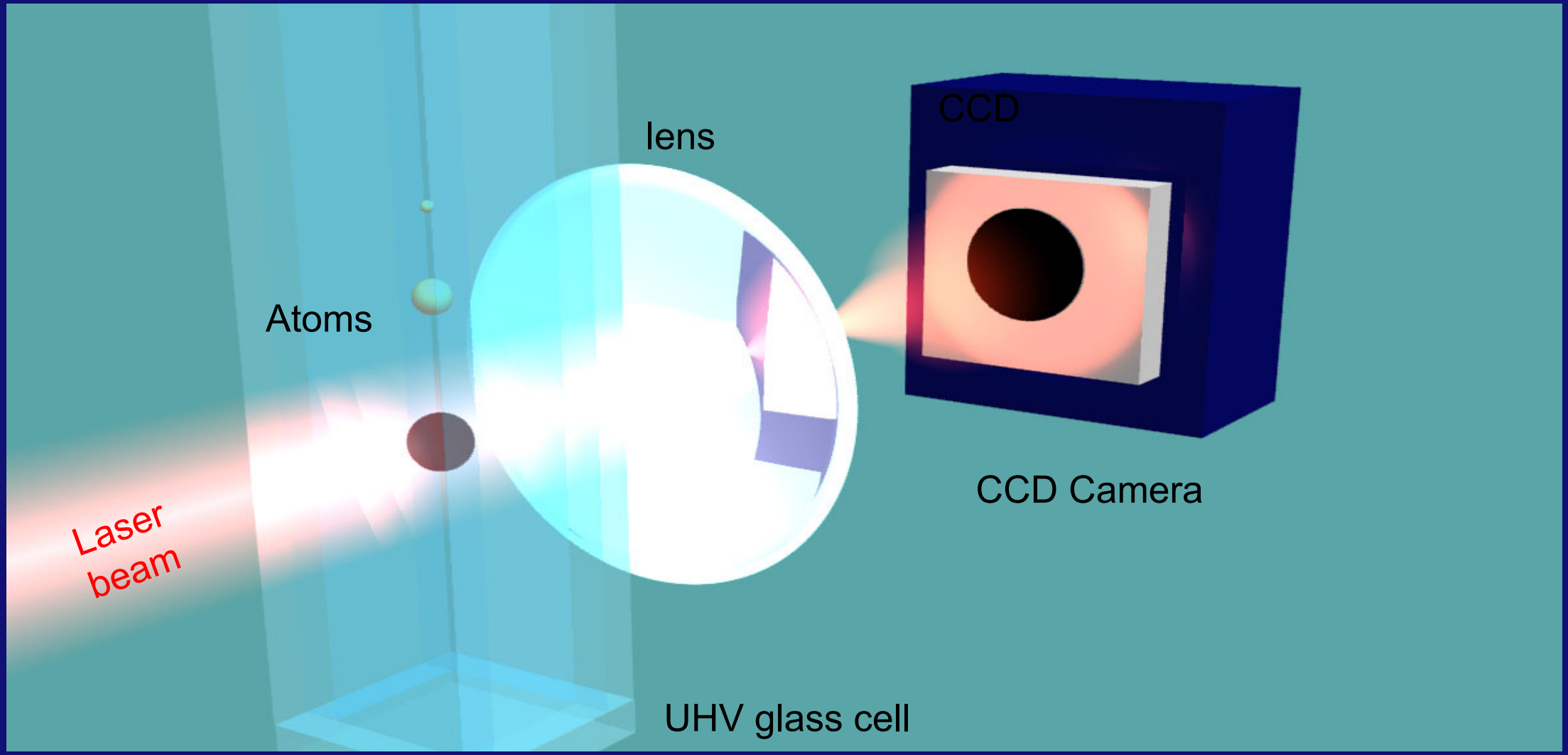
Evaporative Cooling



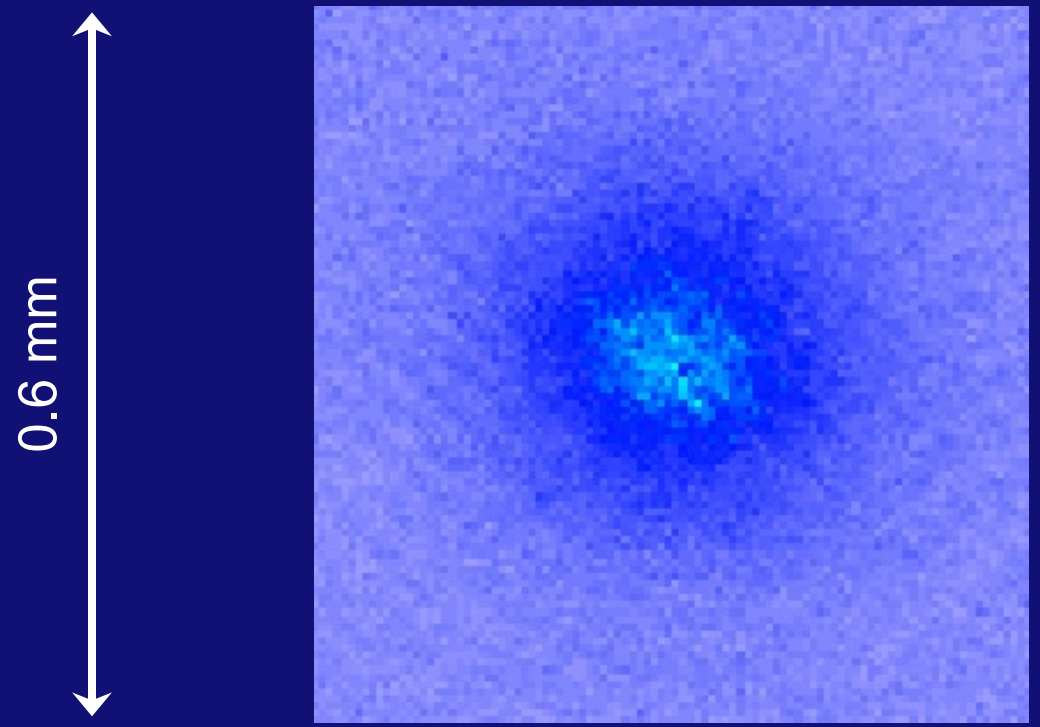


100 nK

Absorption Imaging

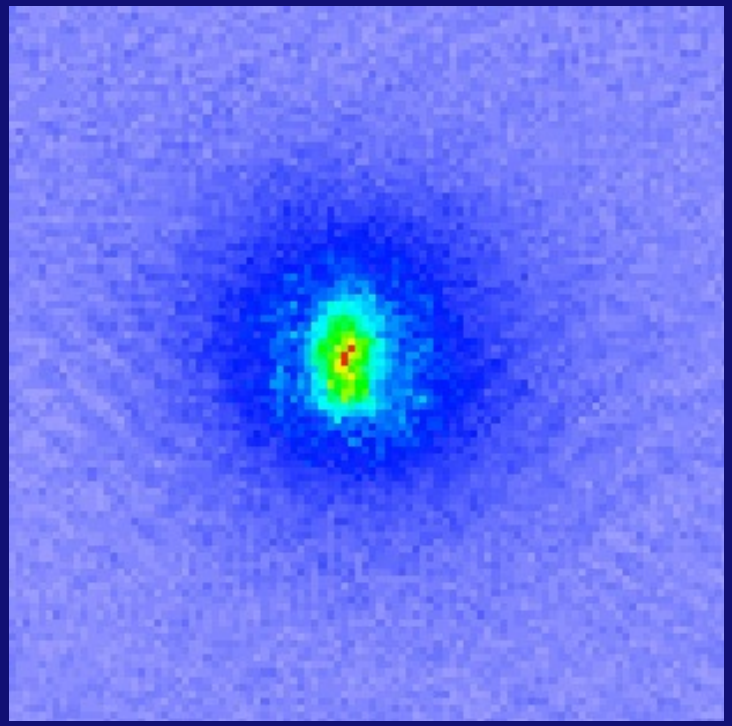


Expansion of a cold gas



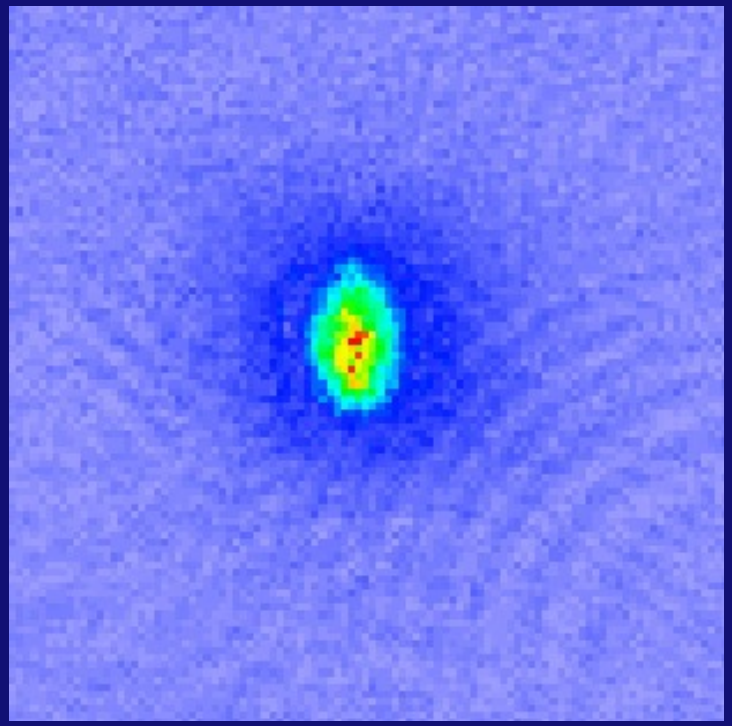
500 nK

Condensation



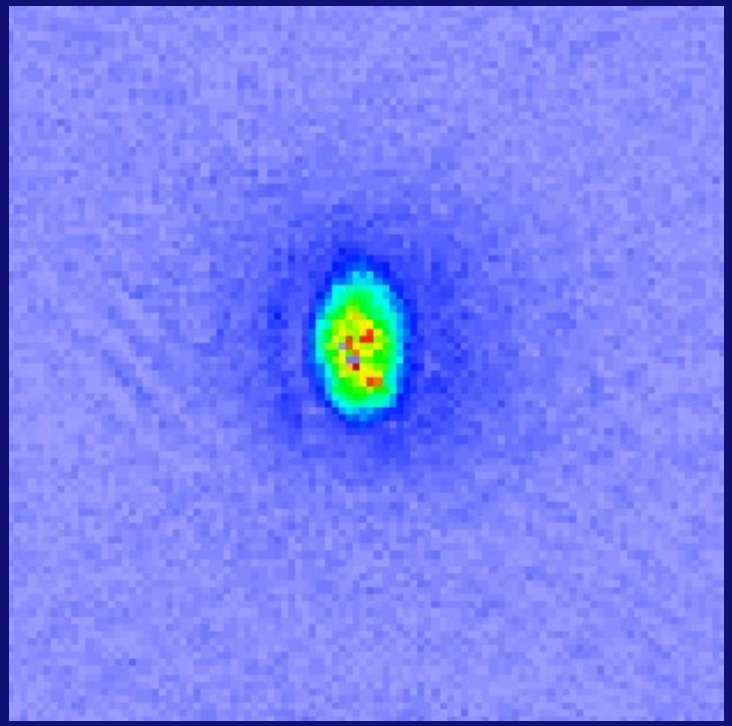
430 nK

Condensation



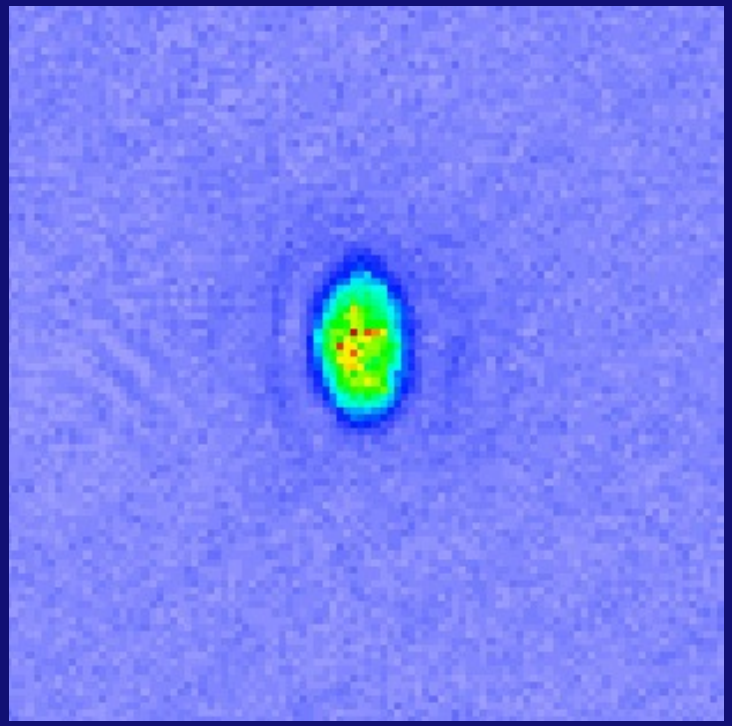
300 nK

Condensation



200 nK

Pure Condensate

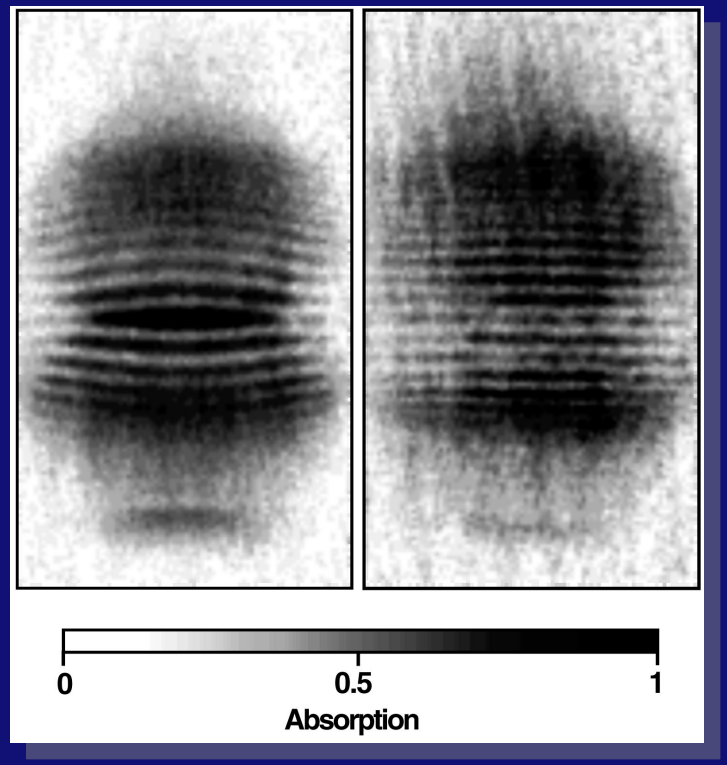


100 nK

Cornell 1995

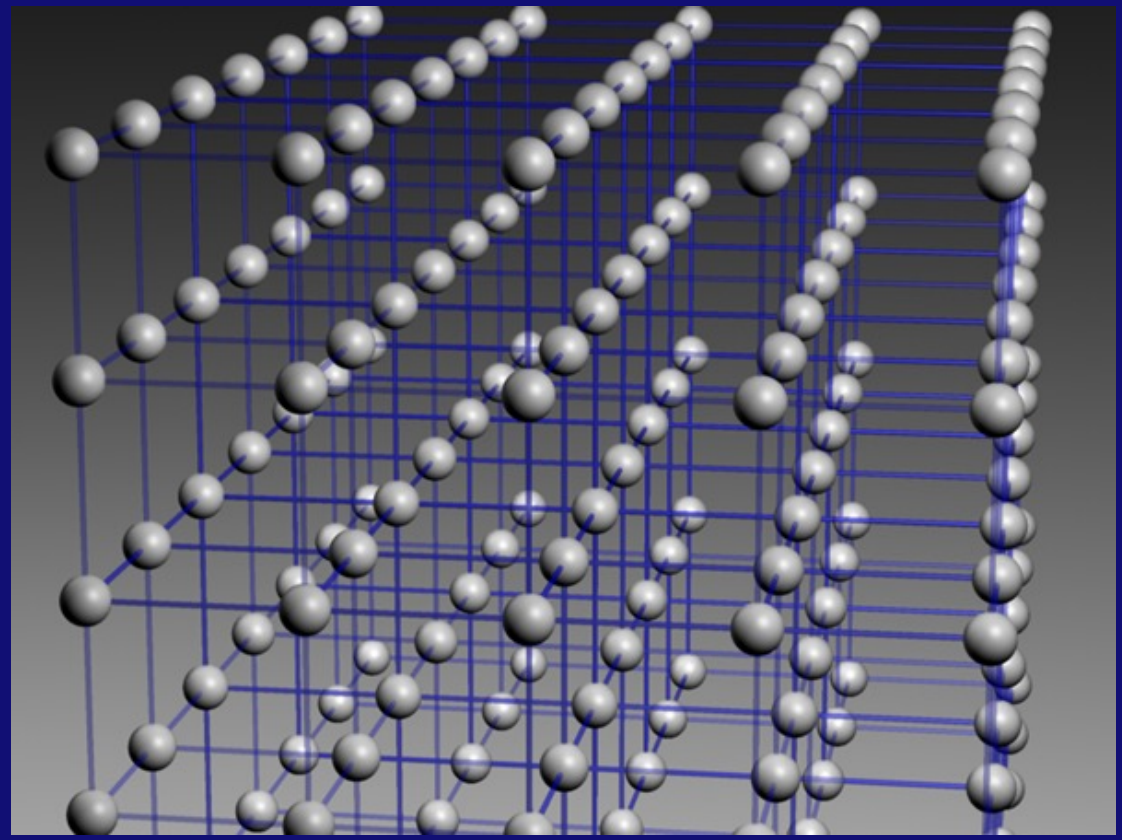
MH Anderson, JR Ensher, MR Matthews, CE Wieman, EA Cornell, Science 269 (5221), 198-201

Wave nature



Ketterle 1997

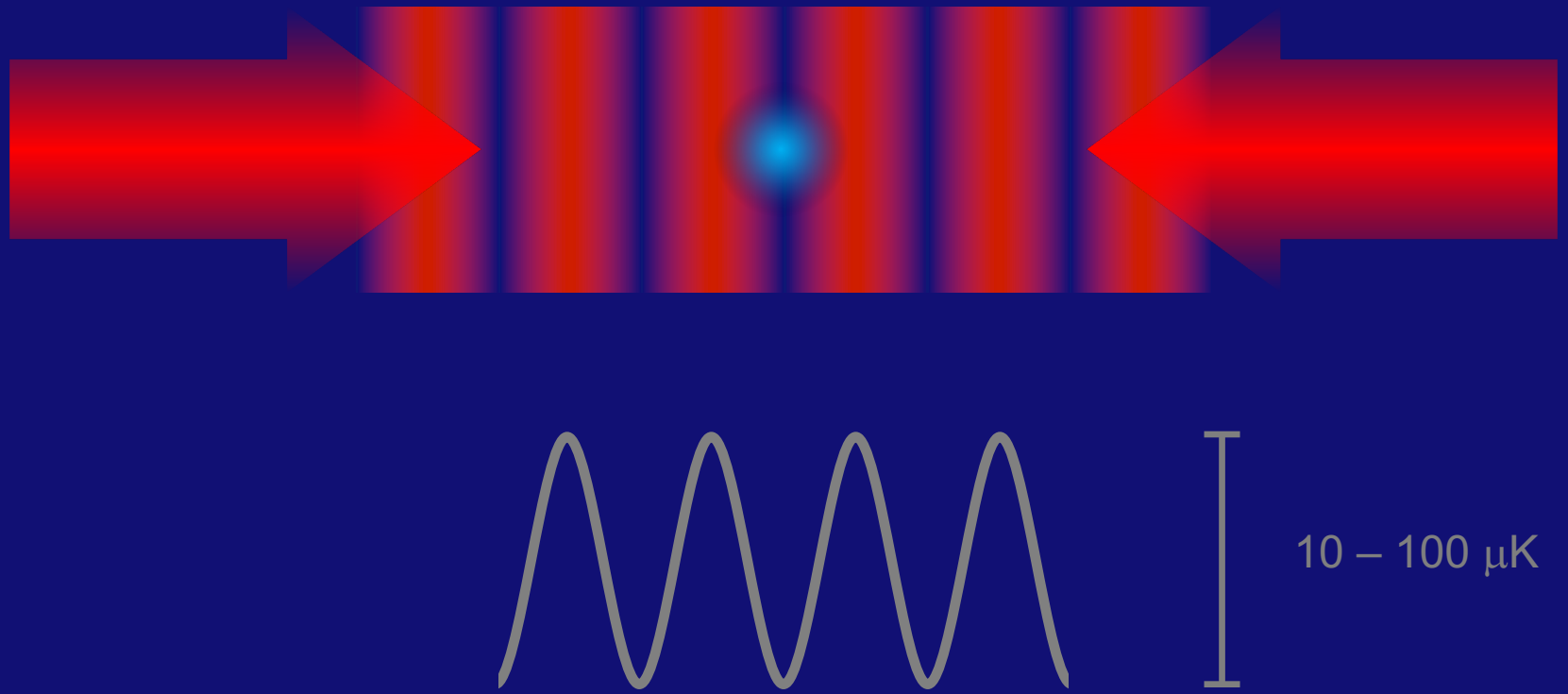
M. R. Andrews, C. G. Townsend, H.-J. Miesner, D. S. Durfee, D. M. Kurn, W. Ketterle, Science 275, 637 (1997).



Matter and Light working together

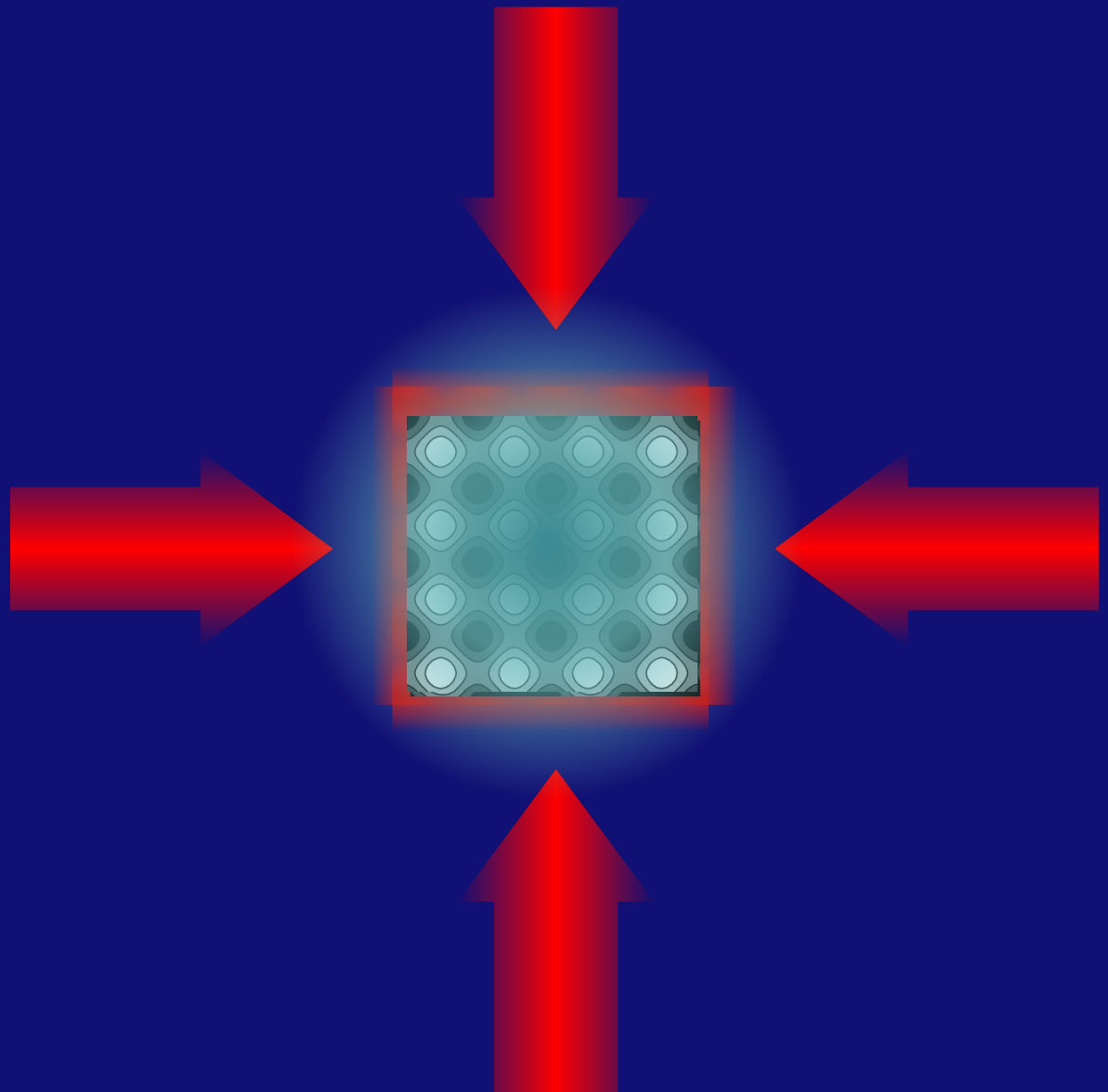
Matter and Light working together

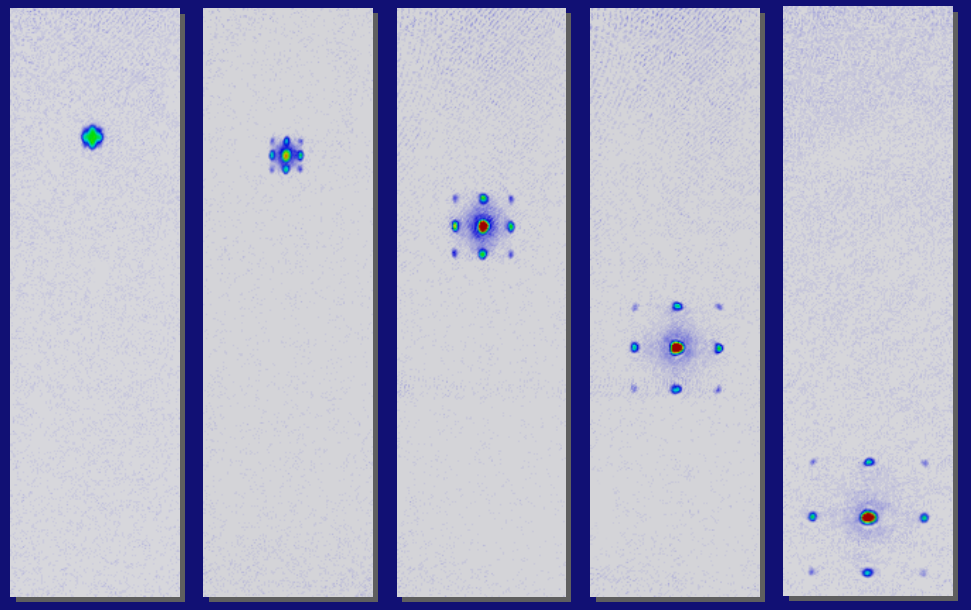
Atoms are polarizable and experience a periodic potential



V. L. Letokhov, “Narrowing of the Doppler width in a standing light wave,” *Pis’maZh. Eksp. Teor. Fiz.*, vol. 7, p. 348, 1968. [JETP Lett. **7**, 272 (1968)].

Matter Waves in Optical Lattices

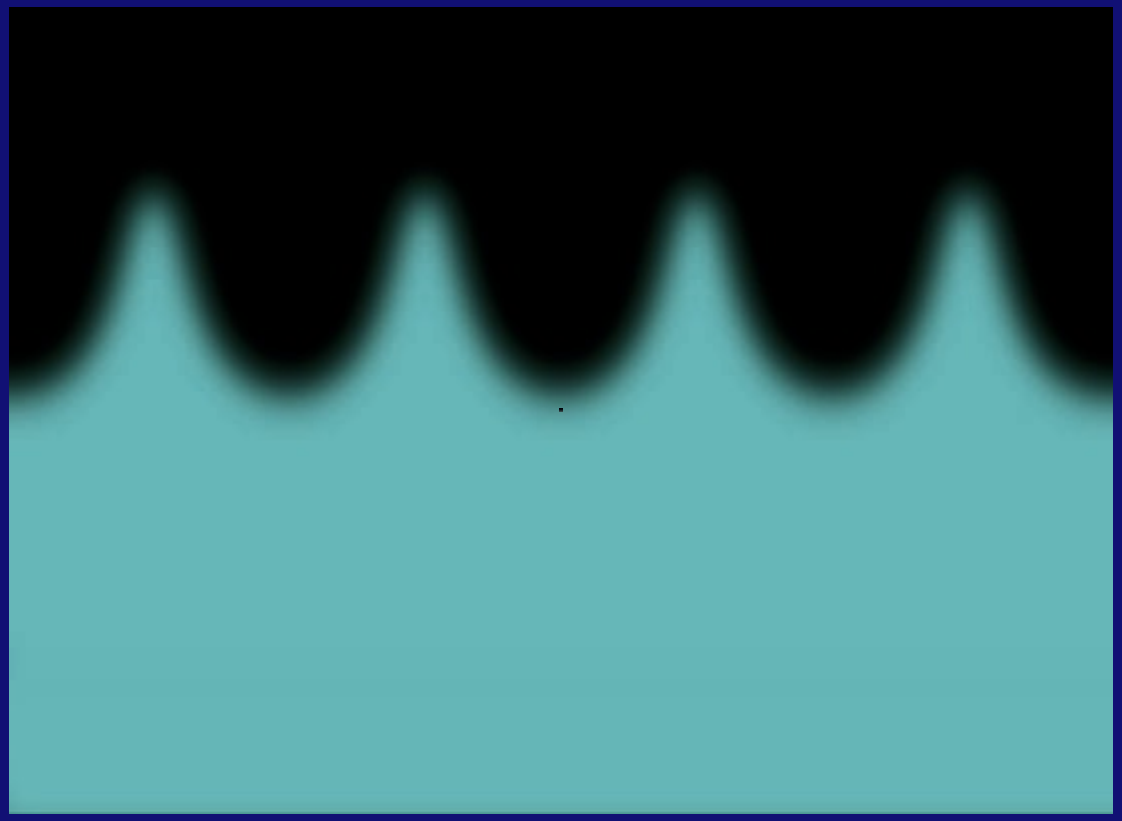




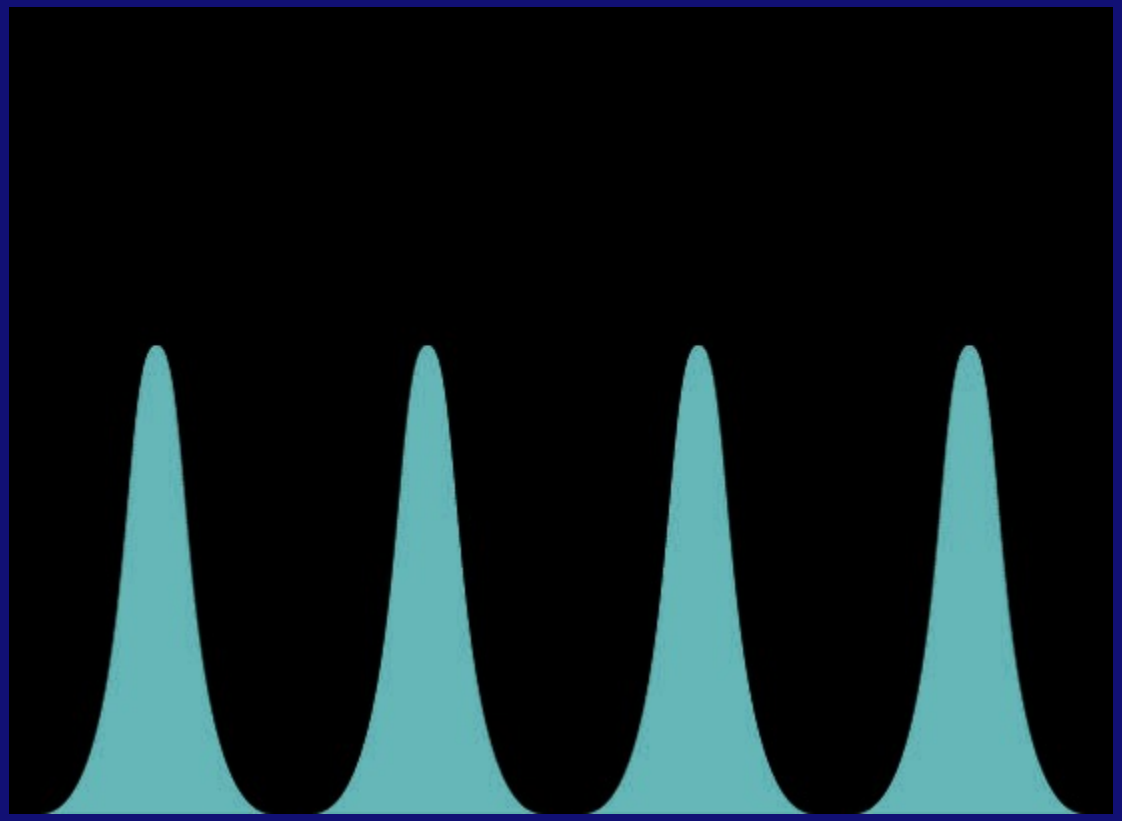
3D: M. Greiner, O. Mandel, T. Esslinger, T. W. Hänsch, and I. Bloch, Nature 415, 39-44 (2002)

2D: M. Greiner, I. Bloch, O. Mandel, T. W. Hänsch, and T. Esslinger, Phys. Rev. Lett. 87, 160405 (2001).

Matter Waves in Optical Lattices

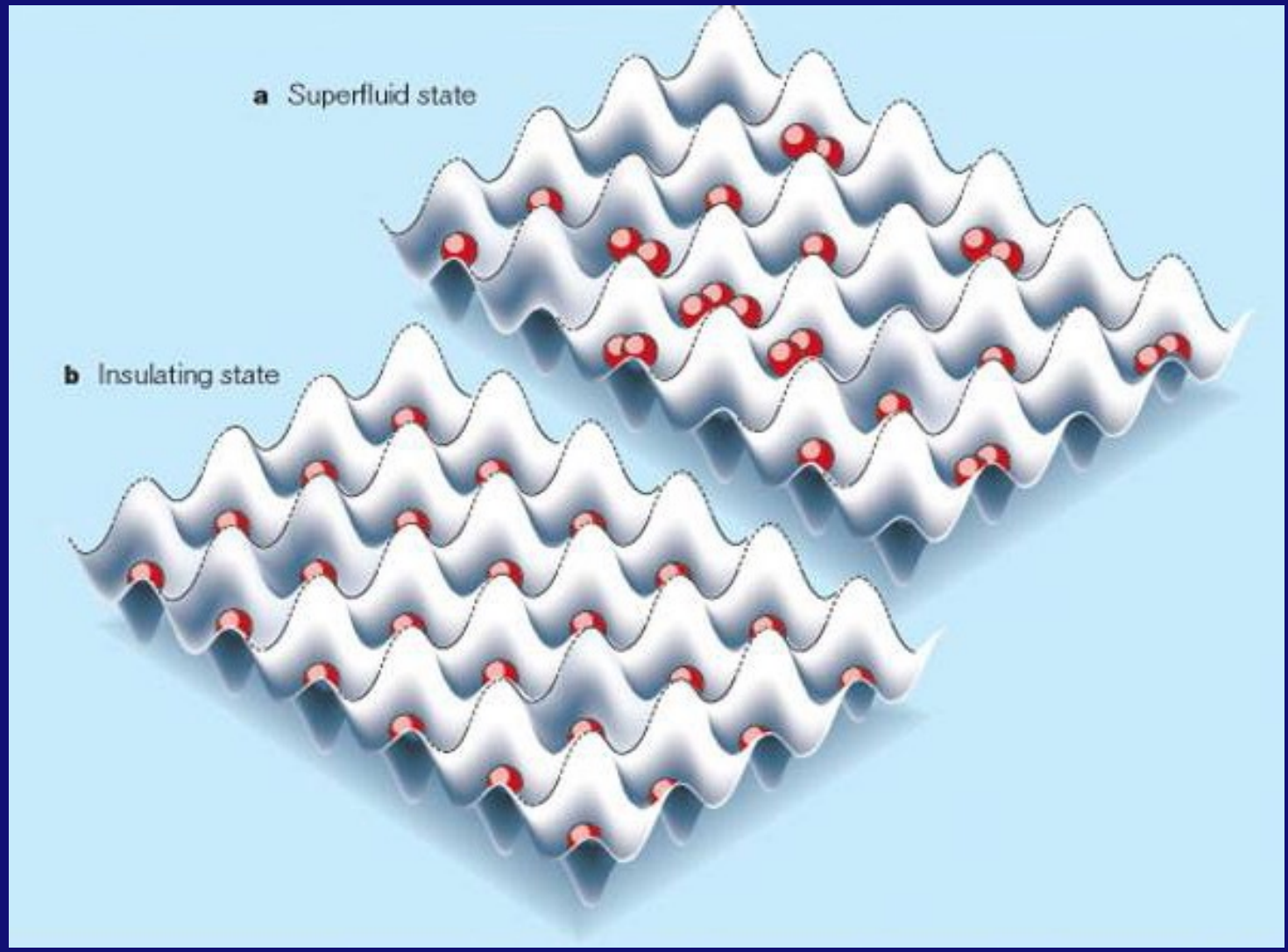


Matter Waves in Optical Lattices

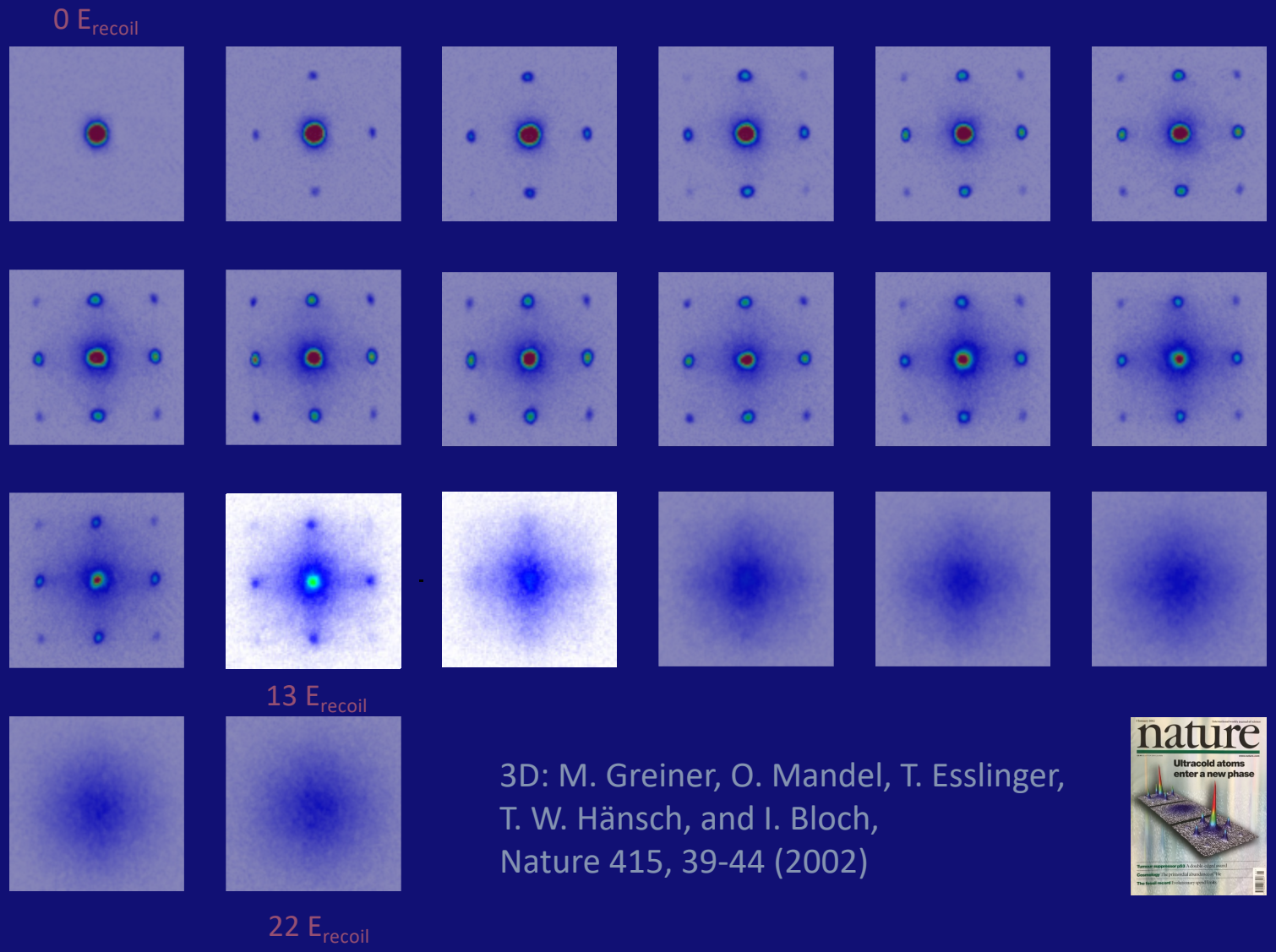


Quantum Phase Transition to the Mott-Insulator

Insulating vs Superfluid state

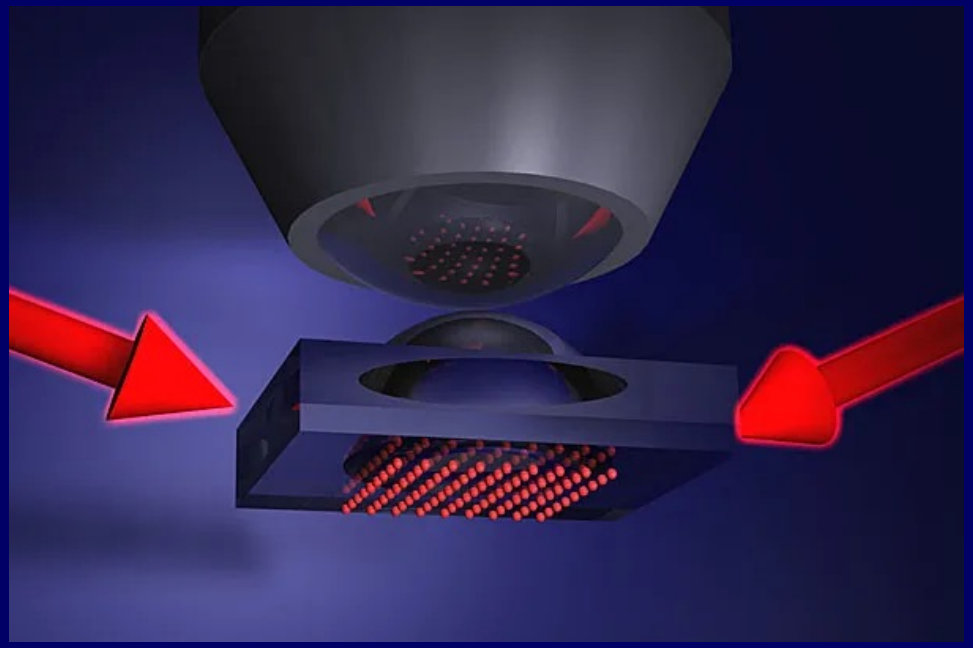


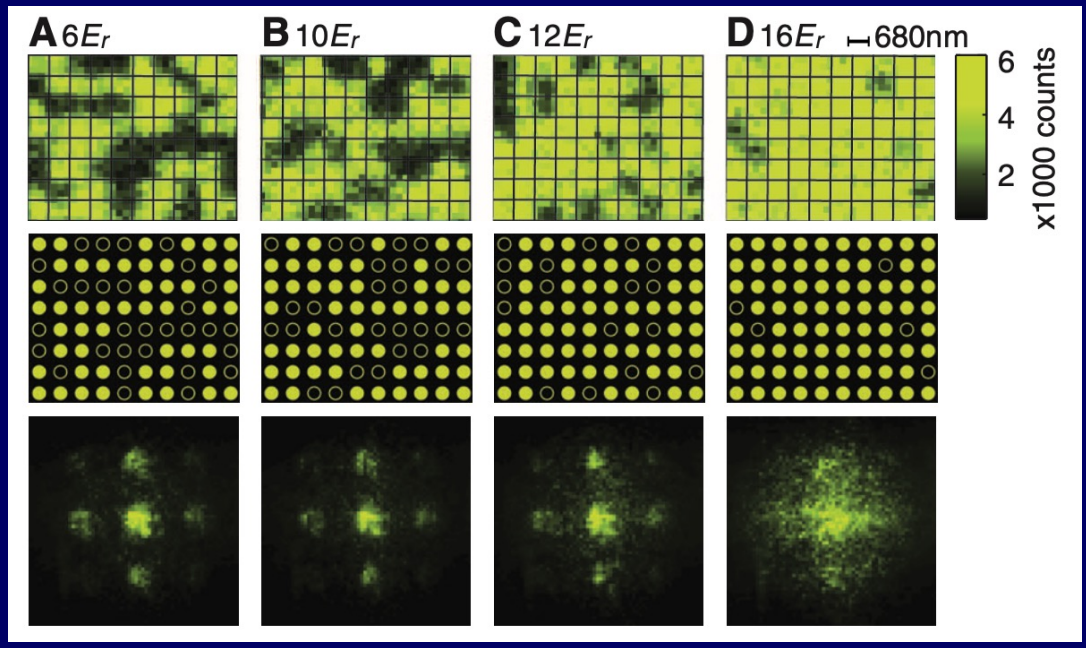
Insulating vs Superfluid state



3D: M. Greiner, O. Mandel, T. Esslinger, T. W. Hänsch, and I. Bloch, Nature 415, 39-44 (2002)

Wave Particle Duality

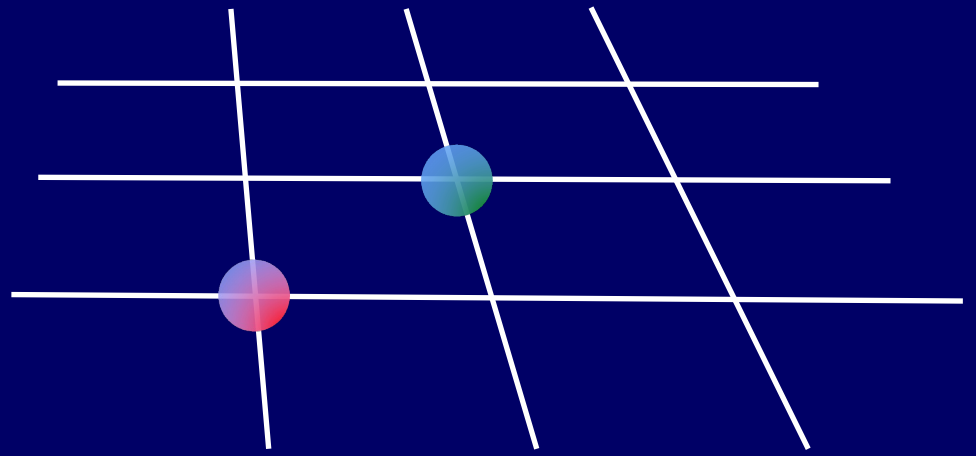




W. S. Bakr, A. Peng, M. E. Tai, R. Ma, J. Simon, J. I. Gillen, S. Fölling, L. Pollet, and M. Greiner, Science 329, 547 (2010)

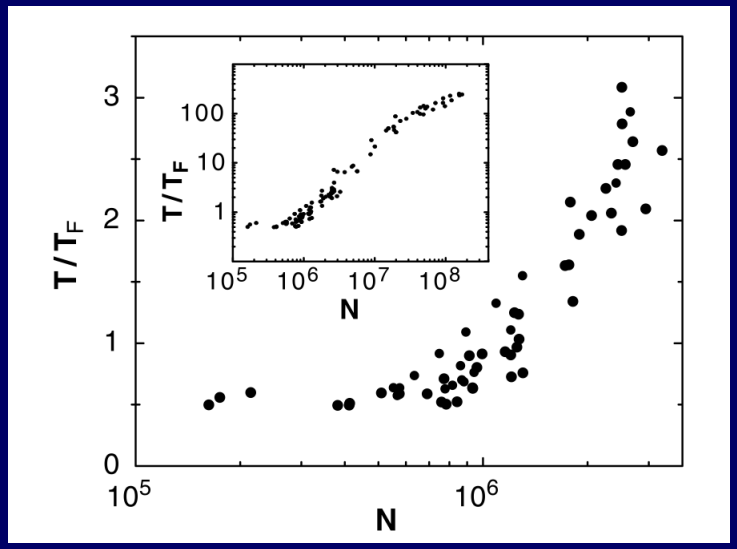
Hubbard Models

$$H = -t \sum_{\{i,j\},\sigma} \hat{c}^{\dagger}_{i,\sigma} \hat{c}_{j,\sigma} + U \sum_{i} \hat{n}_{i,\uparrow} \hat{n}_{i,\downarrow}$$

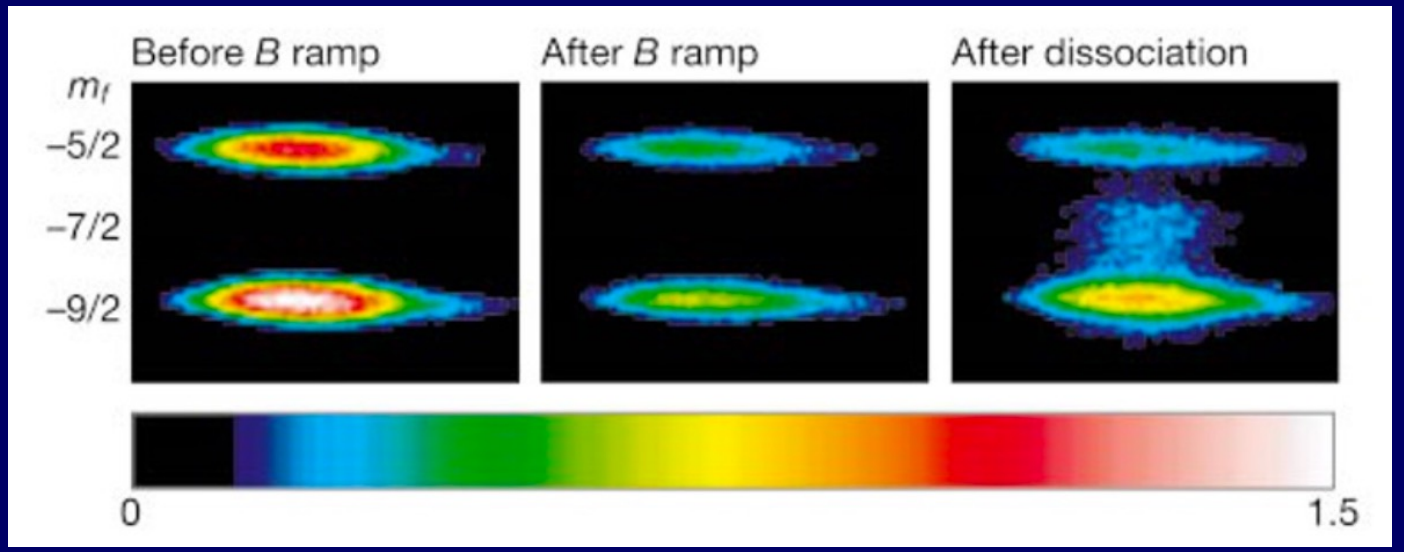


Cold bosonic atoms in optical lattices, D. Jaksch, C. Bruder, J.I. Cirac, C.W. Gardiner, P. Zoller, PRL 81, 3108 (1998)

Quantum Degenerate Fermi Gas



Onset of Fermi Degeneracy in a Trapped Atomic Gas, B. DeMarco and D.S. Jin, Science 285, 1703 (1999)

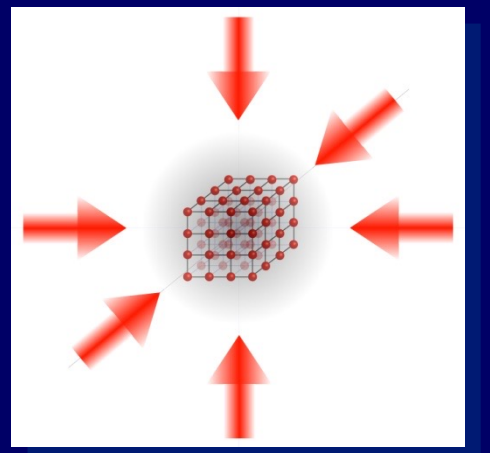


Creation of ultracold molecules from a Fermi gas of atoms, C. A. Regal, C.Ticknor, J.L. Bohn & D.S. Jin, Nature 424, 47 (2003)

Emergence of a molecular Bose–Einstein condensate from a Fermi gas, M. Greiner, C.A. Regal & D. S. Jin Nature 426,(2003).

Fermi-Hubbard Model

+

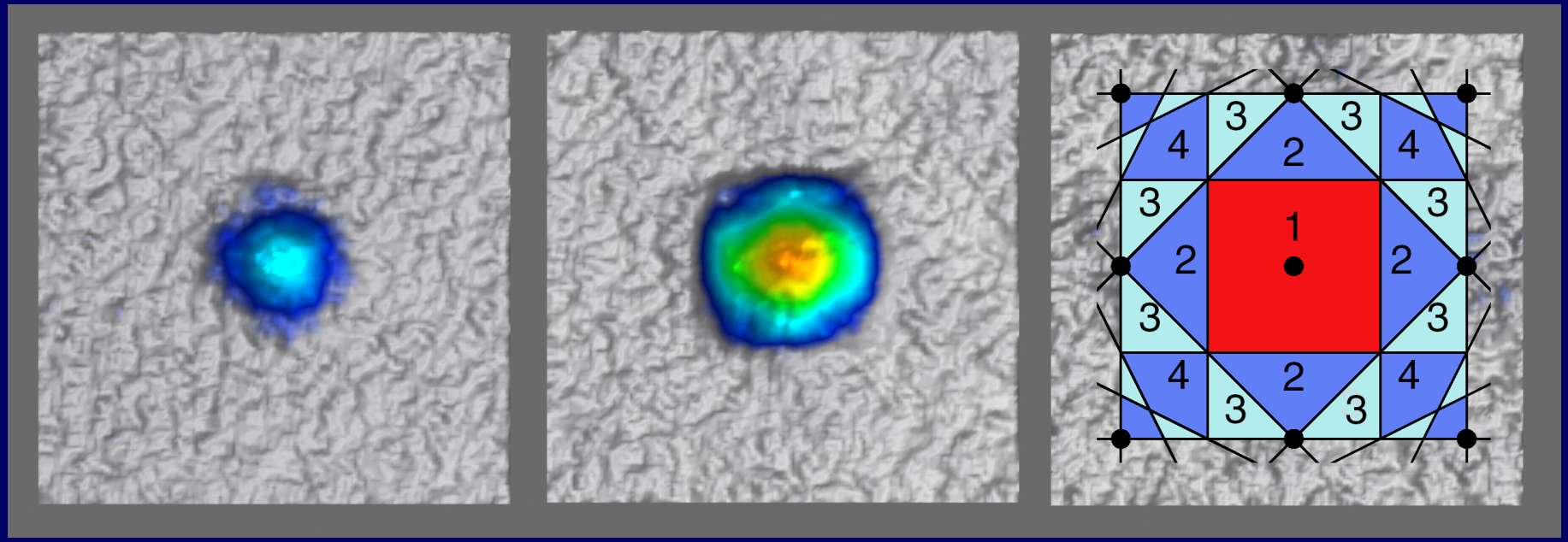


Quantum Gas (^{40}K)

Optical Lattice

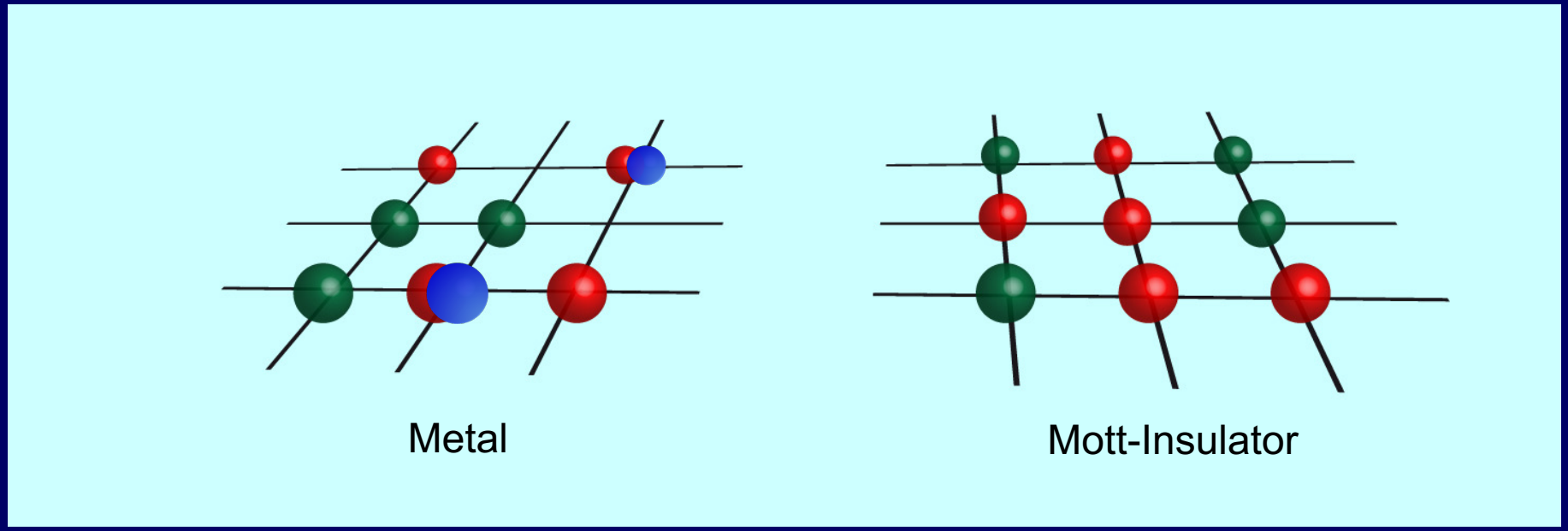
T. Esslinger, Annu. Rev. Condens. Matter Phys. 1 (1), 129-152 (2010)

Measuring Fermi Surfaces



M Köhl, H Moritz, T Stöferle, K Günter, T Esslinger, PRL 94, 080403 (2004)

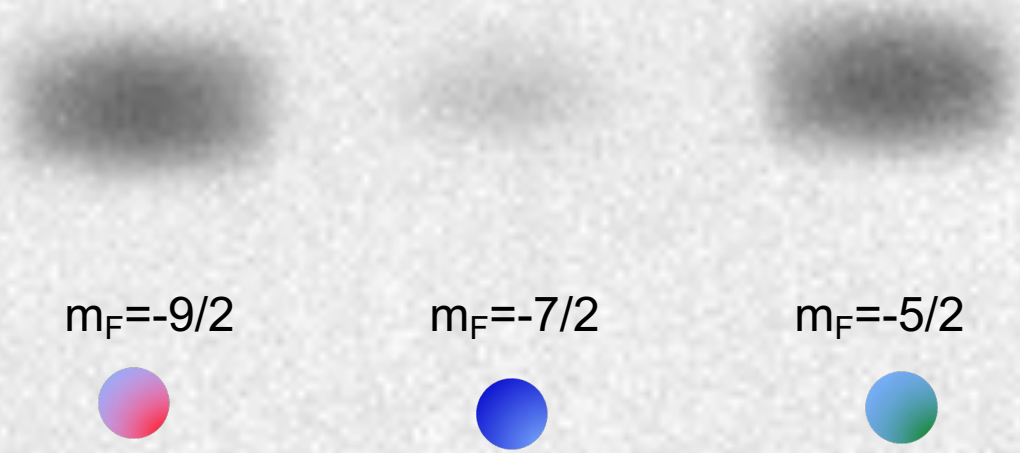
Stern-Gerlach Spectroscopy of Pairs



Interaction shifted transfer into third spin state

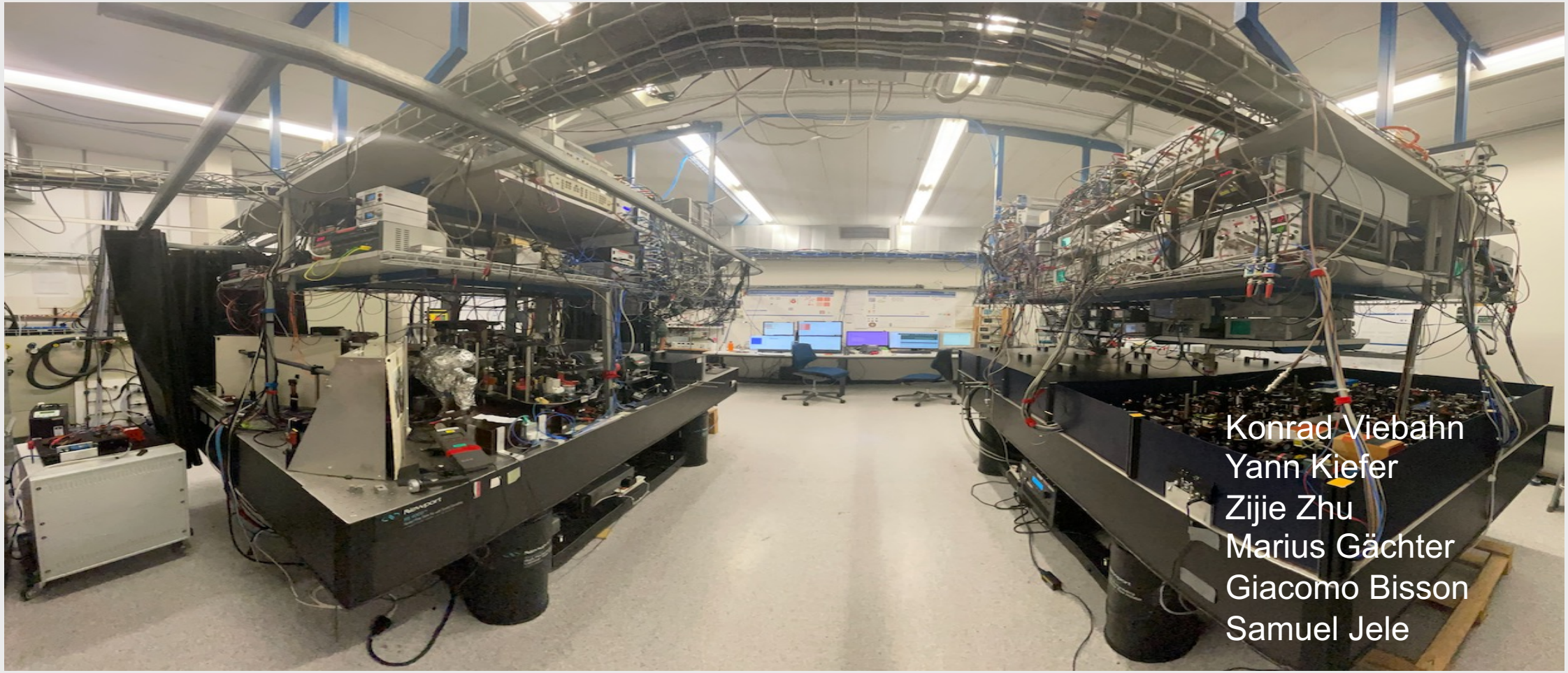
R Jördens, N Strohmaier, K Günter, H Moritz, T Esslinger, Nature 455, 204 (2008)

Stern-Gerlach Spectroscopy of Pairs

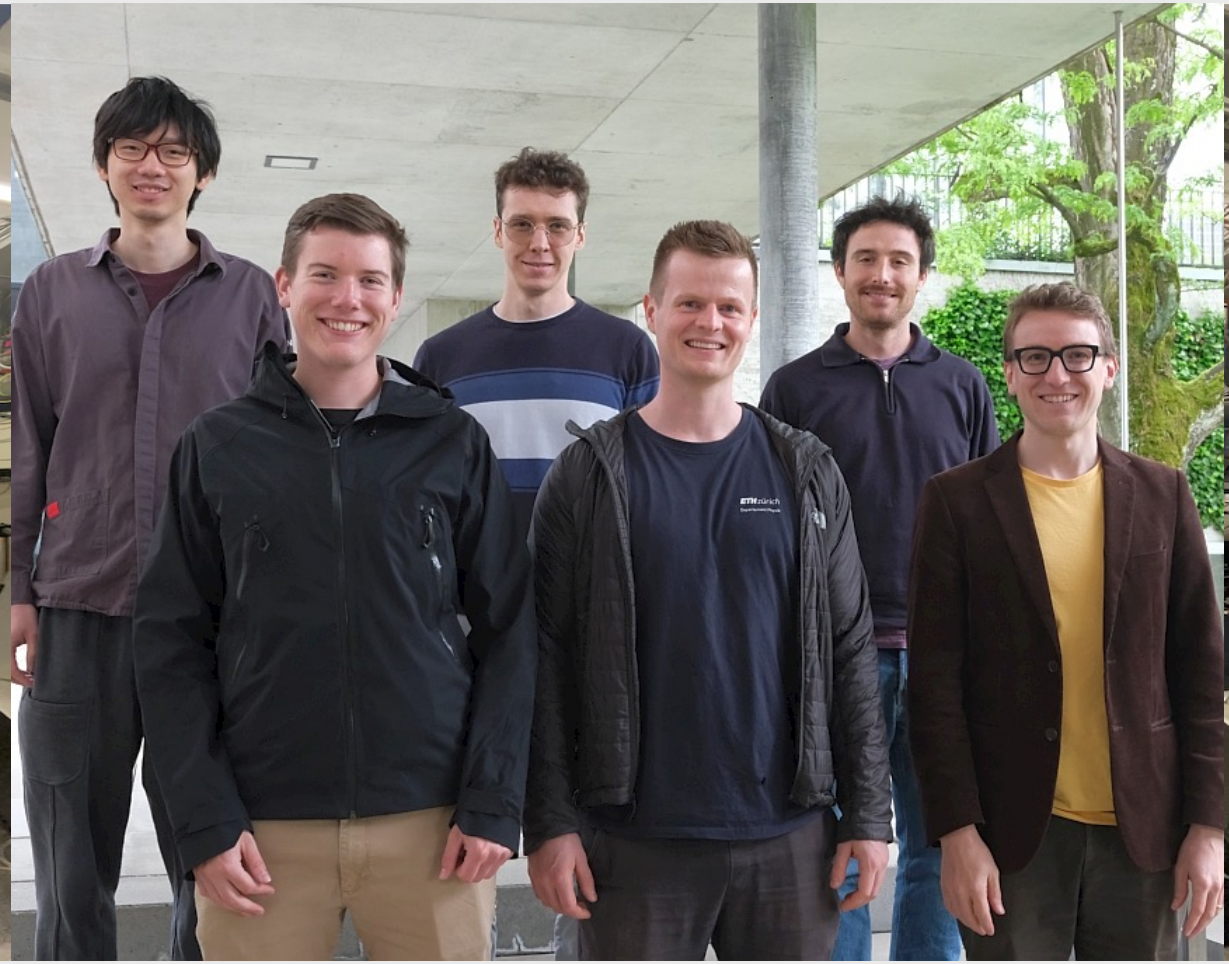


R Jördens, N Strohmaier, K Günter, H Moritz, T Esslinger, Nature 455, 204 (2008)

The Experiment



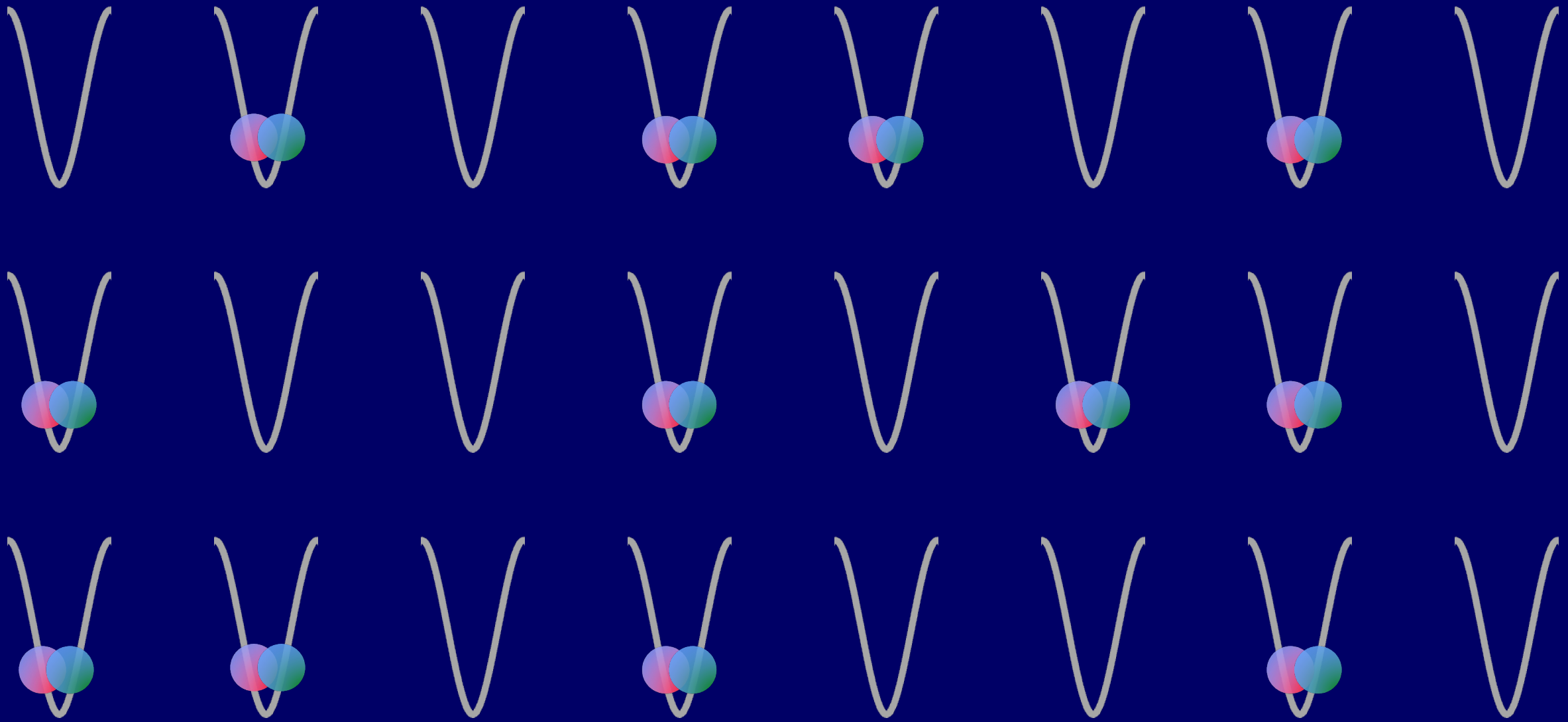
The Team



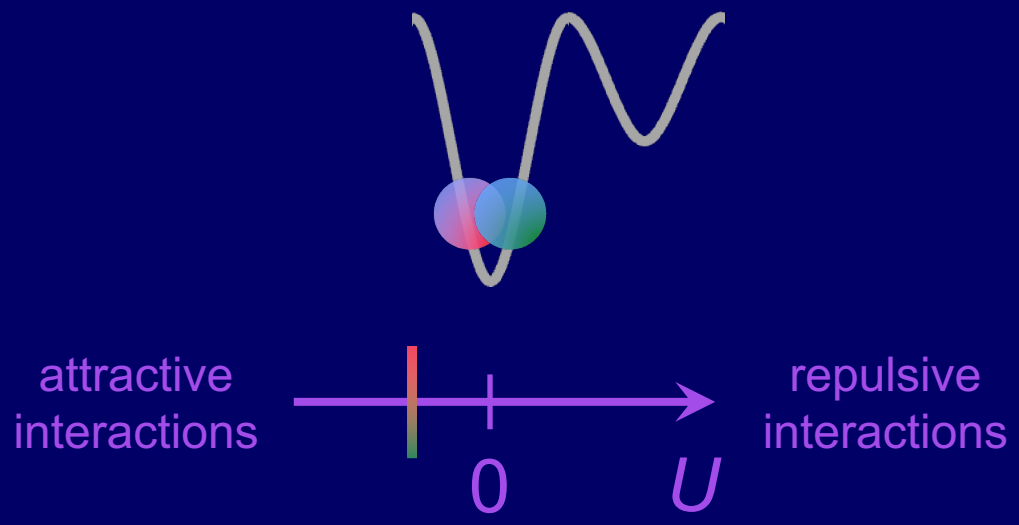
Konrad Viebahn
Yann Kiefer
Zijie Zhu
Marius Gächter
Giacomo Bisson
Samuel Jele

Recent former team members: Anne-Sophie Walter, Kilian Sandholzer, Joaquín Minguzzi

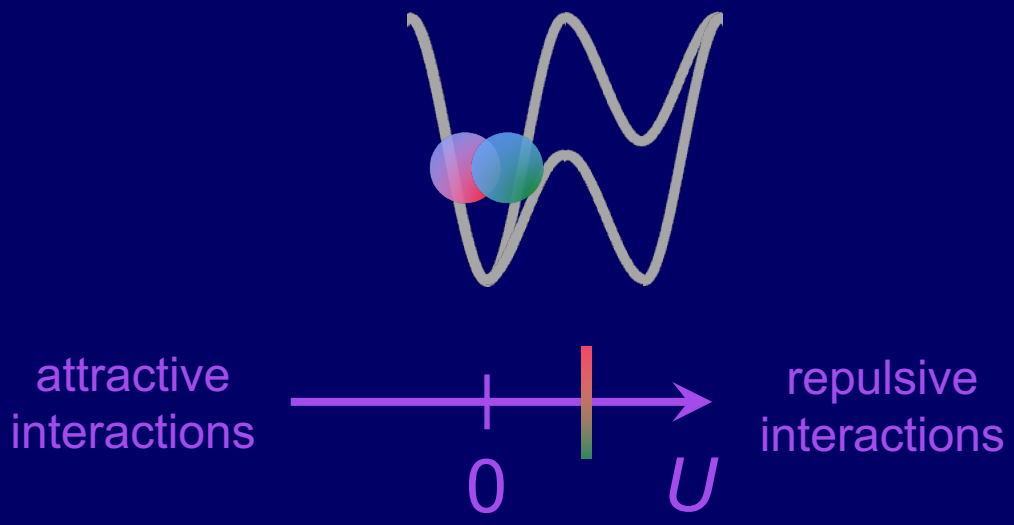
Singlet pairs in a lattice



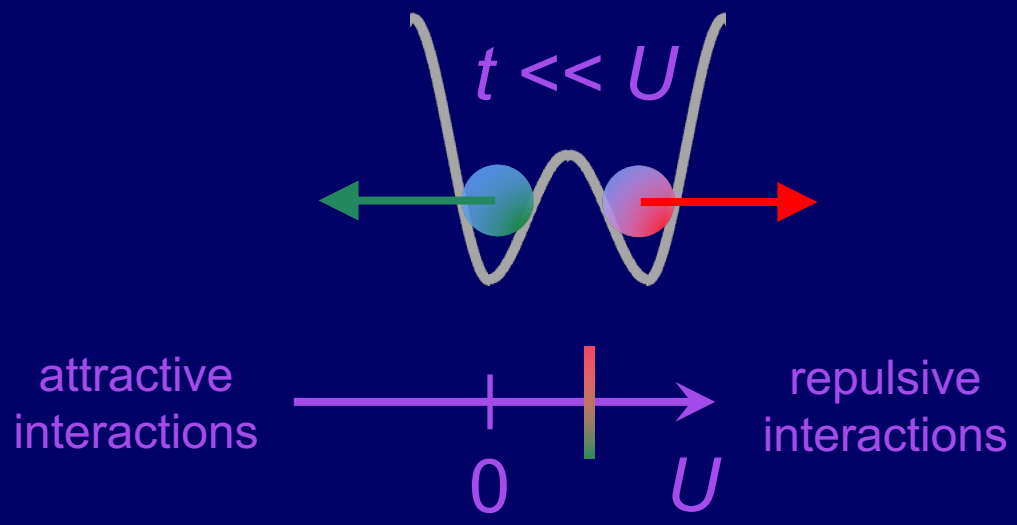
Splitting a singlet pair



Splitting a singlet pair

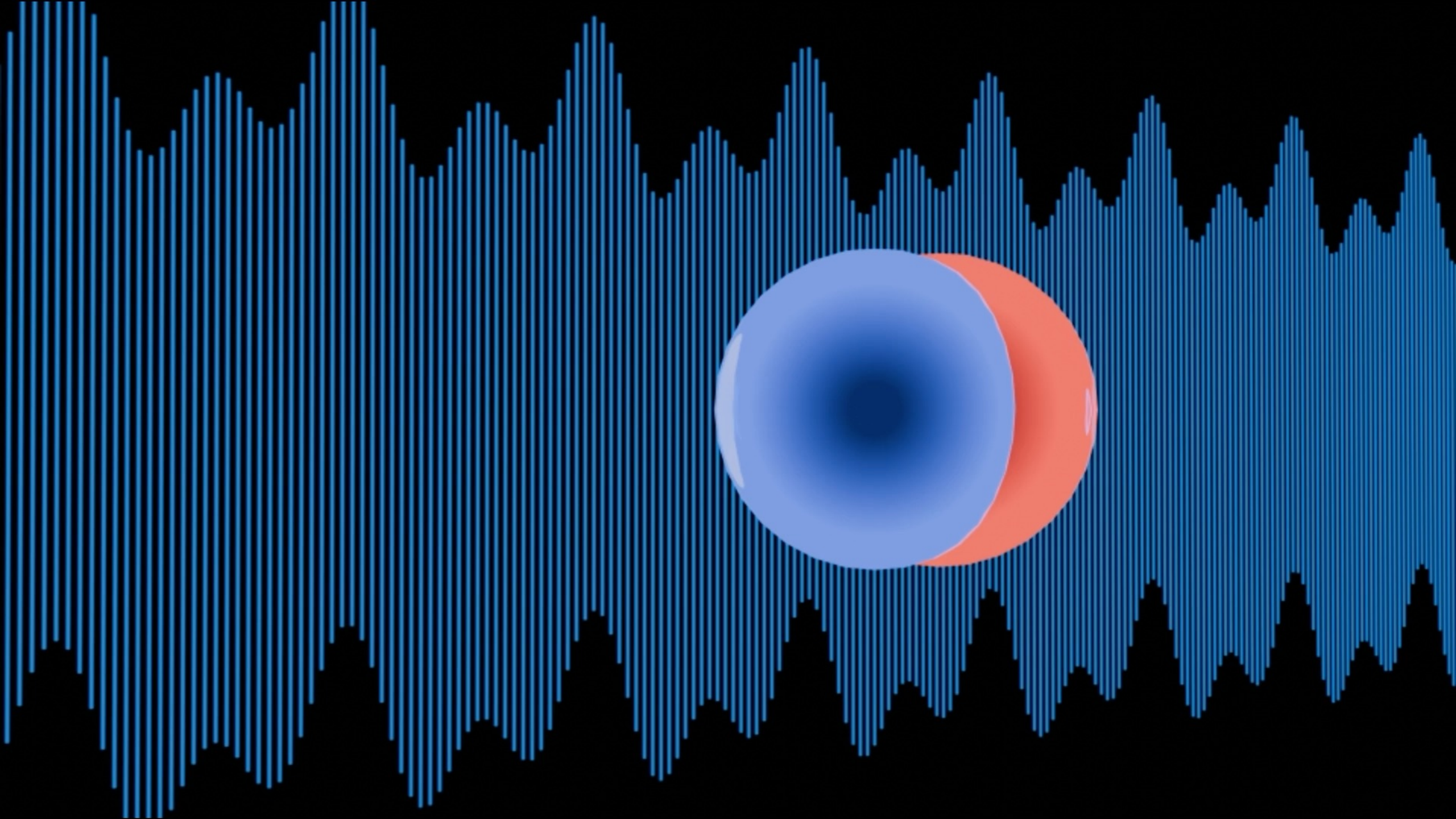


Splitting a singlet pair

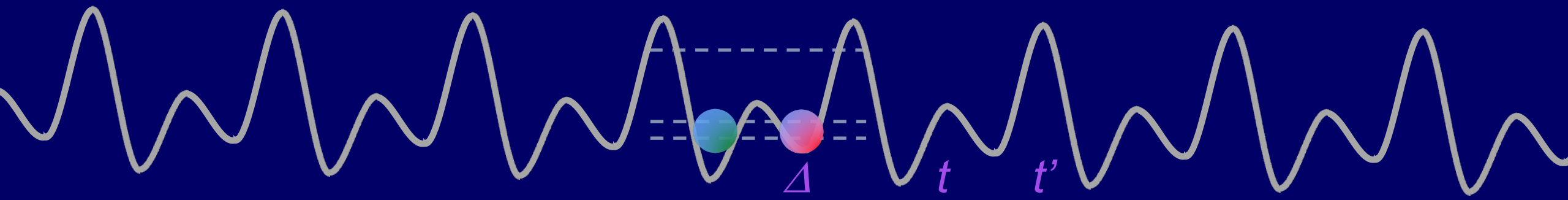


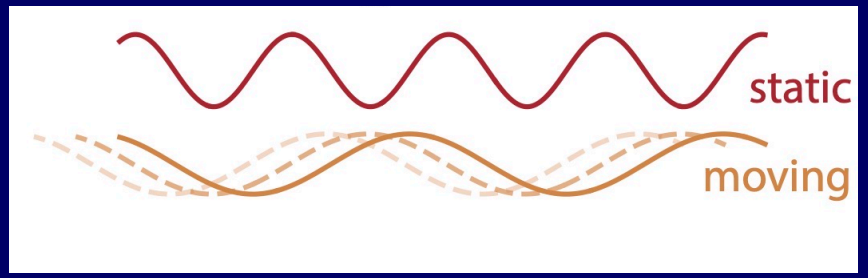
Correlated Bell state

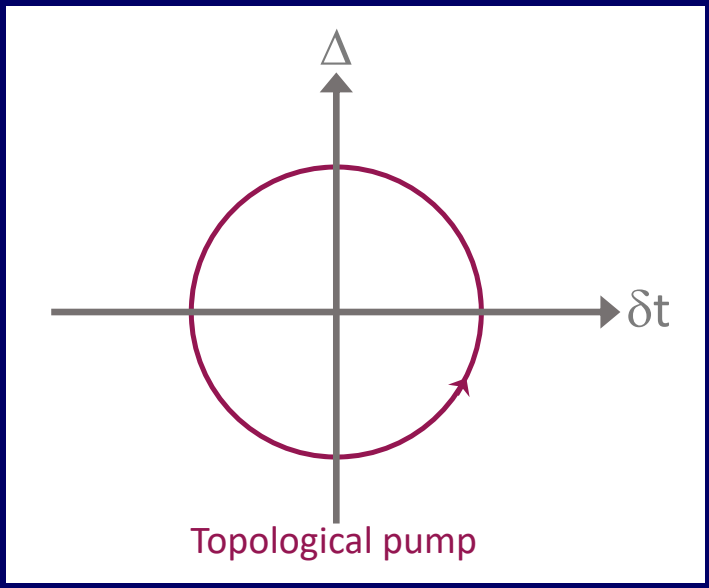
$$(|\downarrow,\uparrow\rangle - |\uparrow,\downarrow\rangle) / 2$$



Topological Pumping



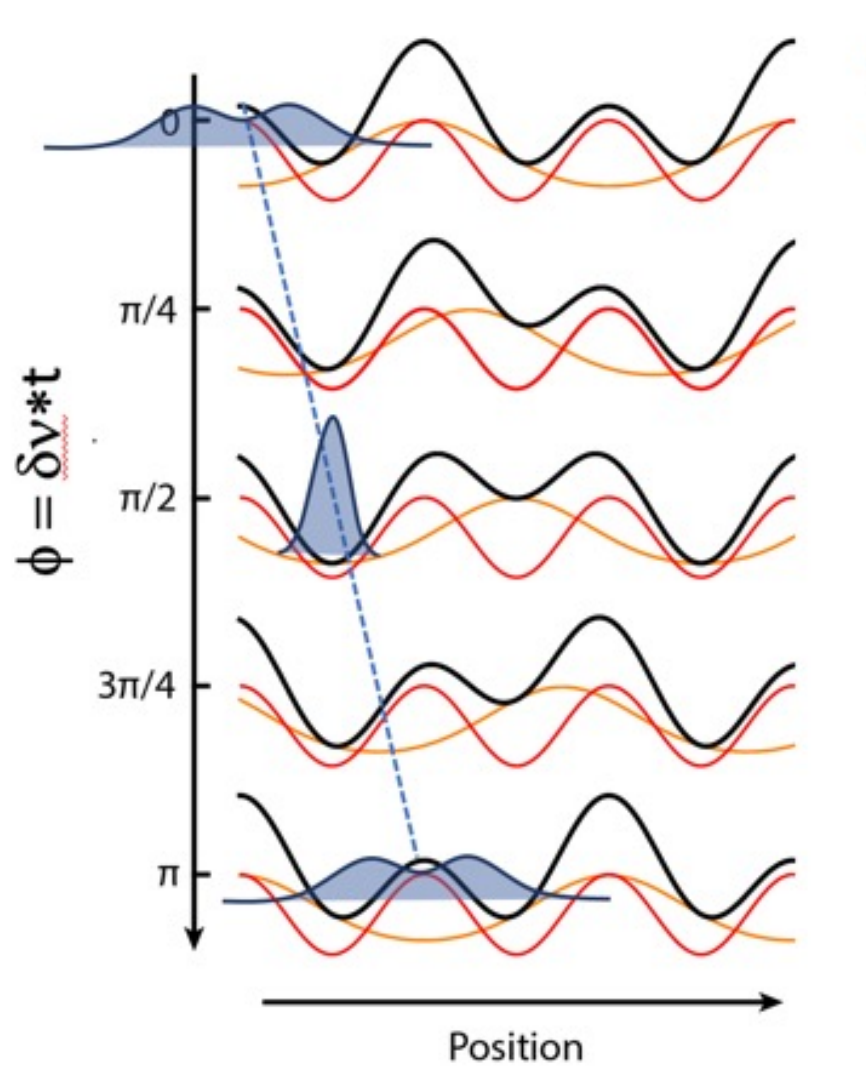


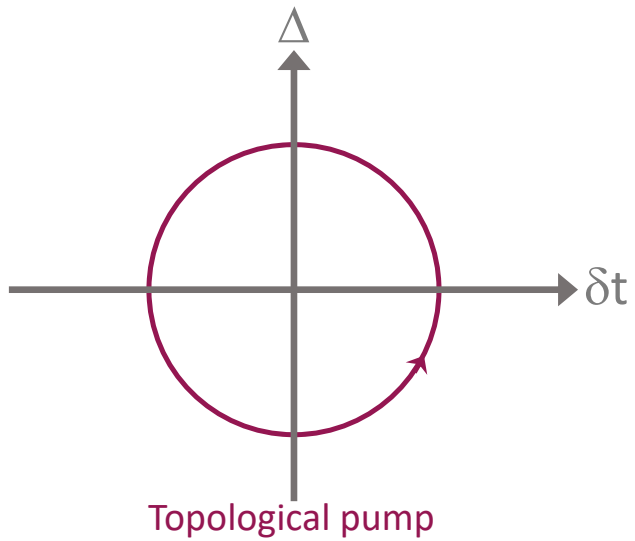


Transport insulating and localized states

Q Niu and D J Thouless 1984 *J. Phys. A: Math. Gen.* **17** 2453
Lei Wang, Matthias Troyer, and Xi Dai, PRL 111, 026802 (2013)

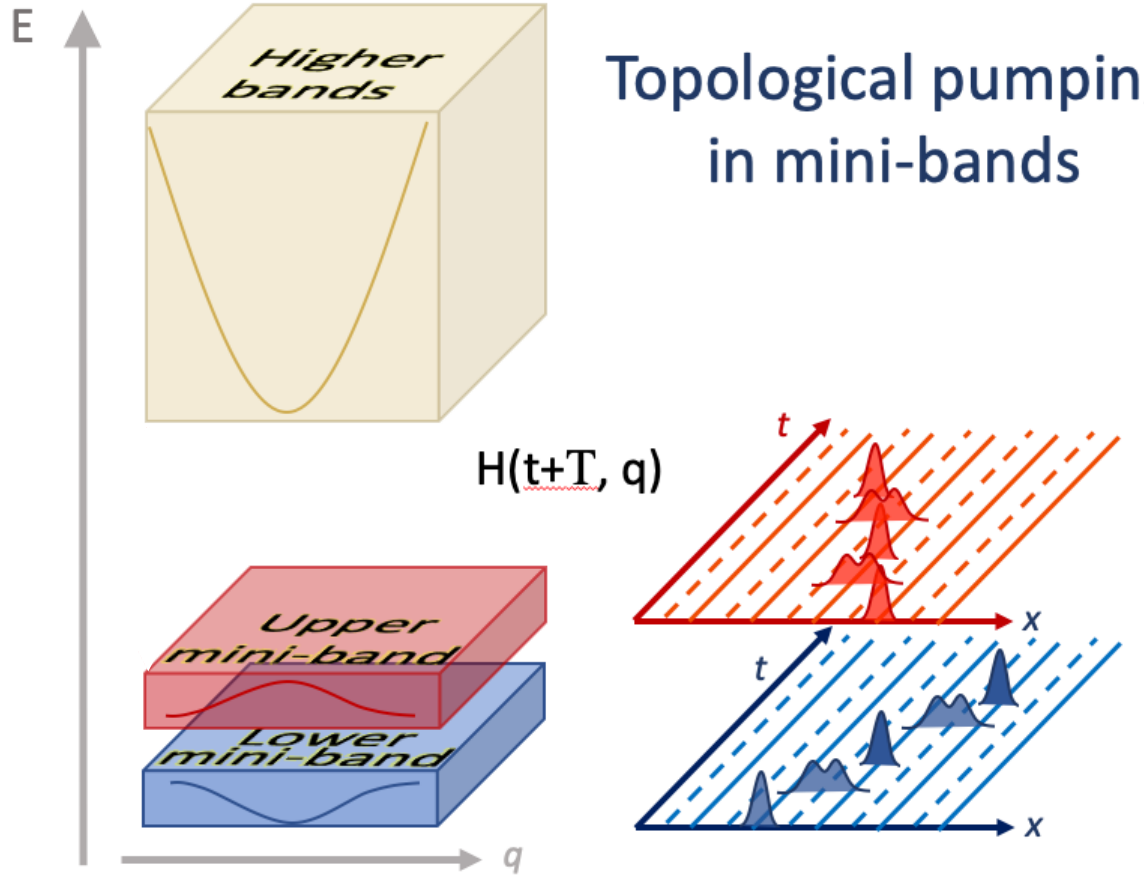
Topological Pumping

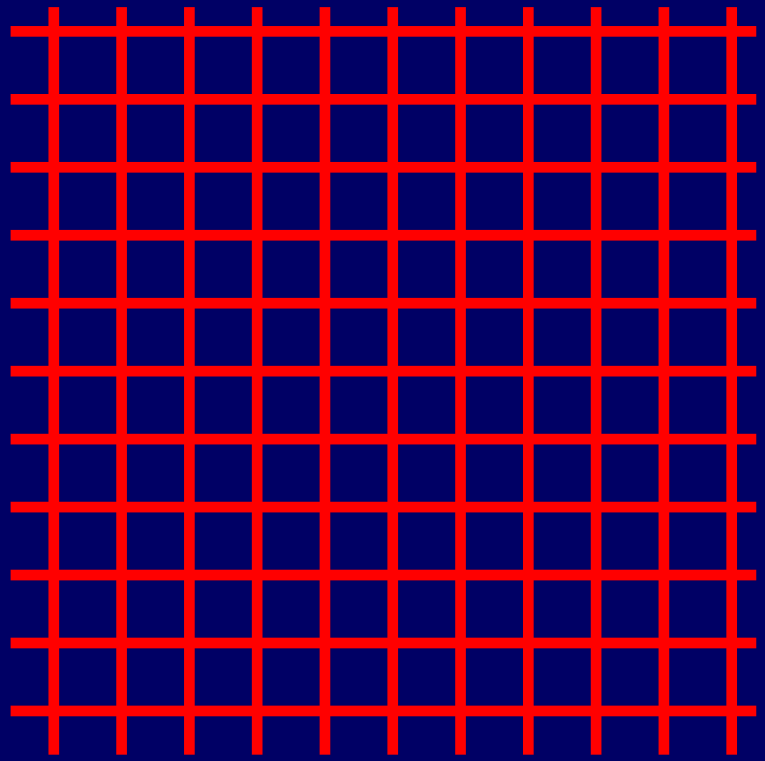


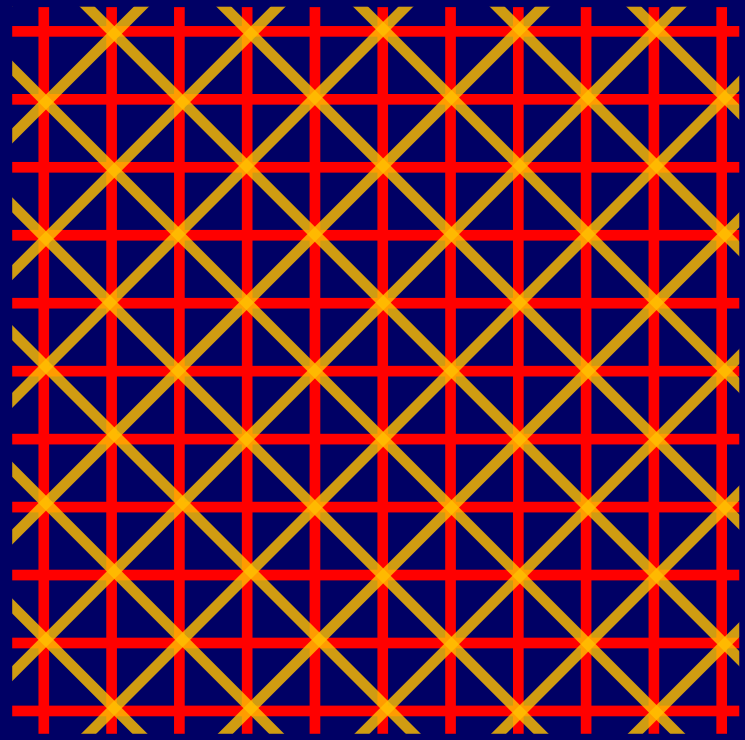


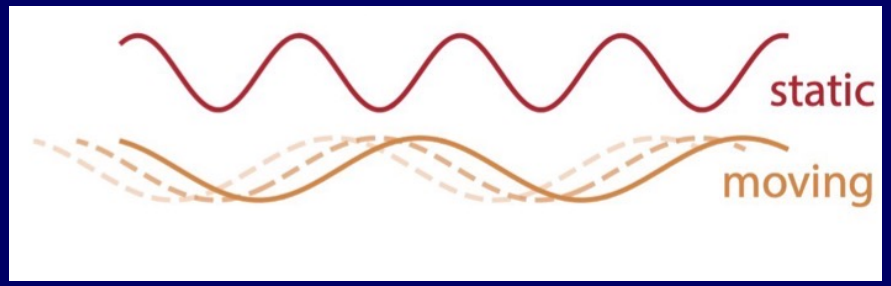
Experiments: Lohse et al. Nat. Phys. 12, 296 (2016) , Aidelsburger/Bloch
Nakajima et al. Nat. Phys. 12, 350 (2016), Takahashi

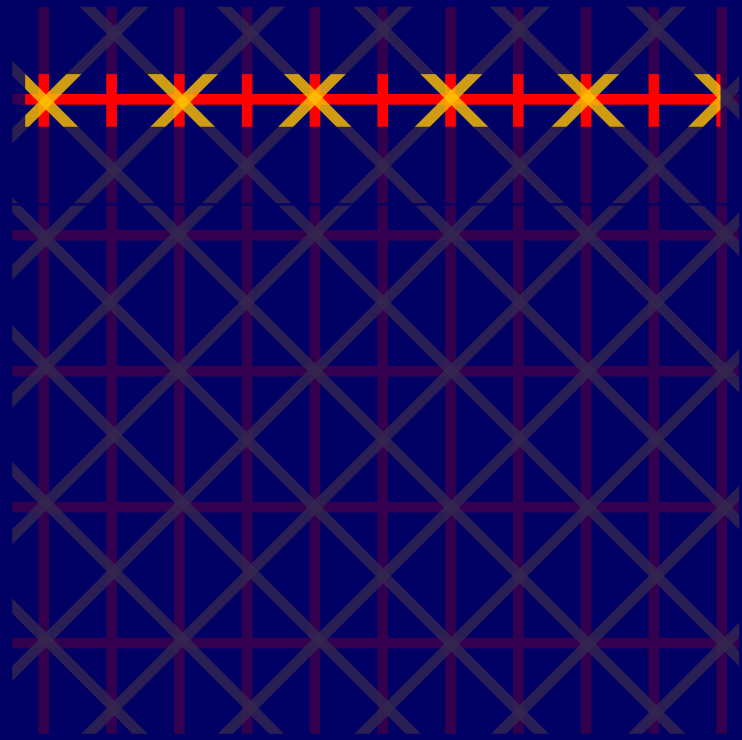
Topological Pumping

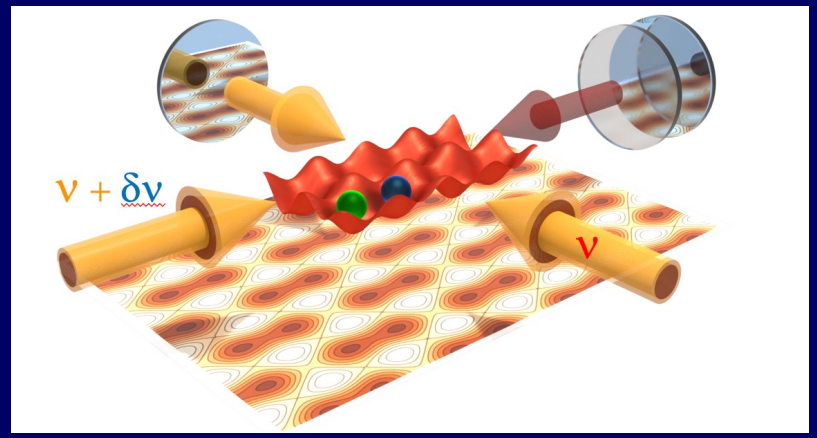


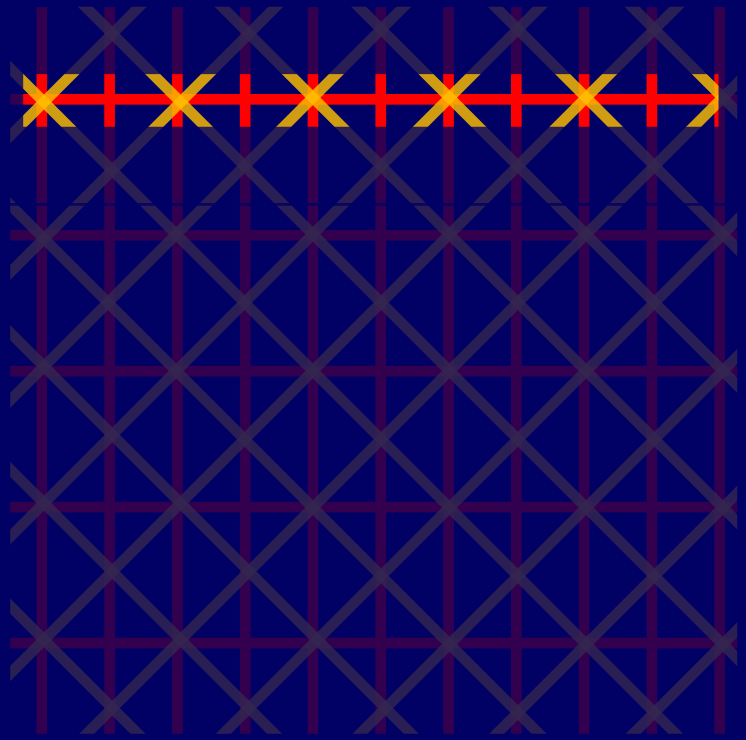




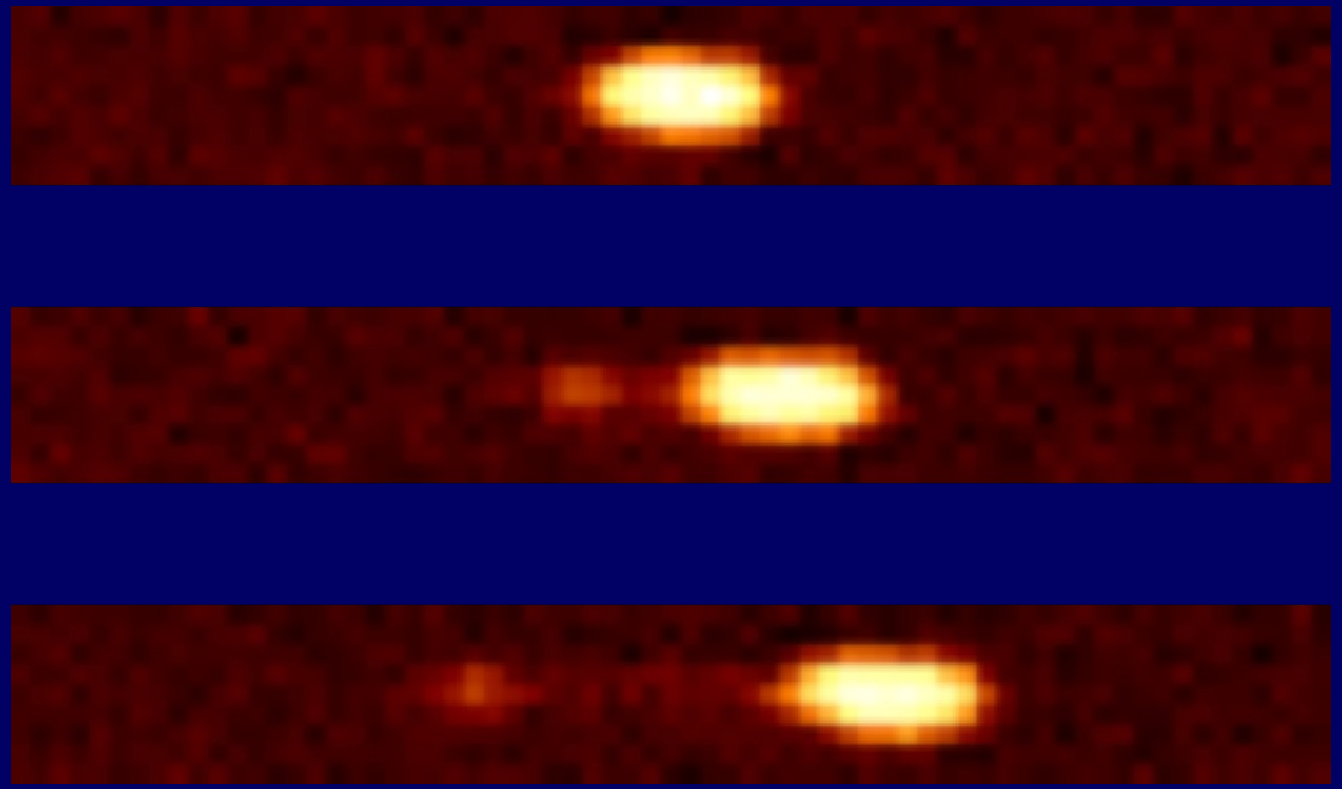

static
moving




ν + δν
ν

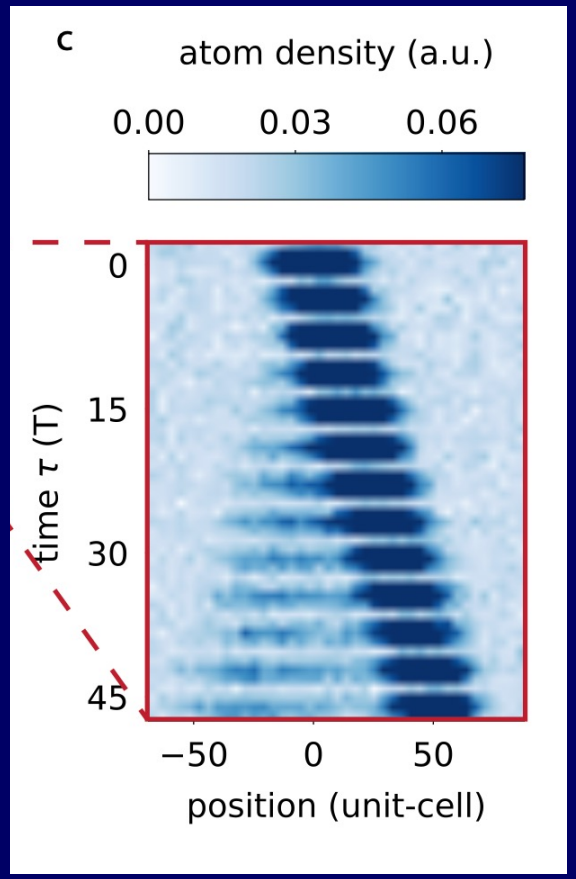


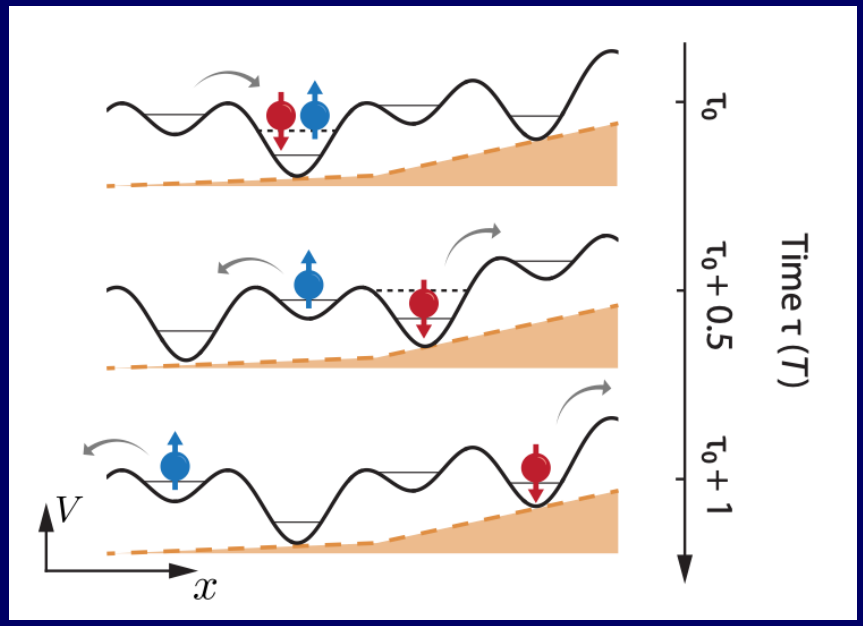
Dynamic Lattice Topological Pump



Quantization and its breakdown in a Hubbard–Thouless pump
Anne-Sophie Walter, Zijie Zhu, Marius Gächter, Joaquín Minguzzi, Stephan Roschinski, Kilian Sandholzer, Konrad Viebahn, Tilman Esslinger, Nature Physics 19 , 1471 (2023).

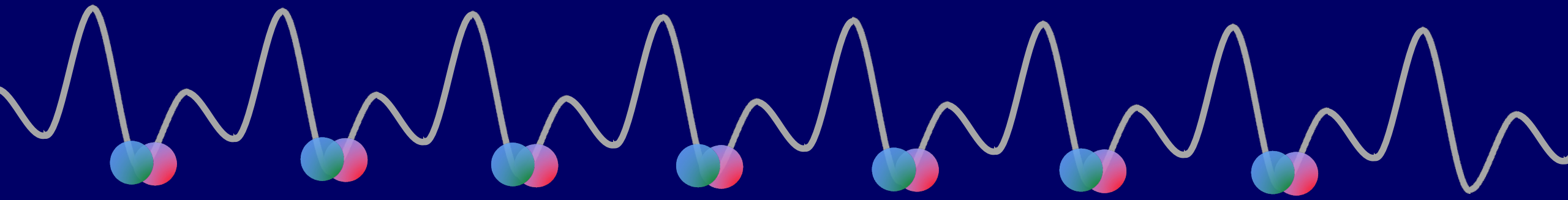
Topological Pumping and interaction induced boundaries

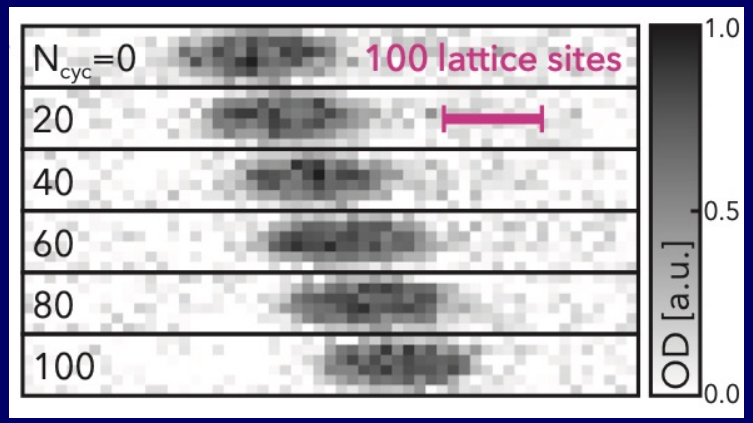


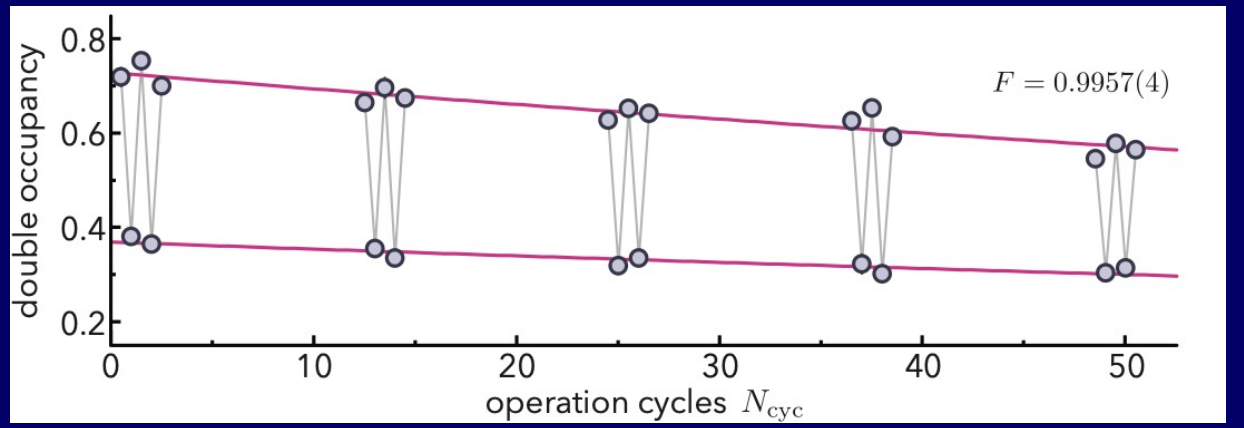


Reversal of quantized Hall drifts at noninteracting and interacting topological boundaries
Z. Zhu, M. Gächter, A.S. Walter, K. Viebahn, T. Esslinger
Science 384, 317 (2024).

All together: Topological Pumping of pairs at U=0



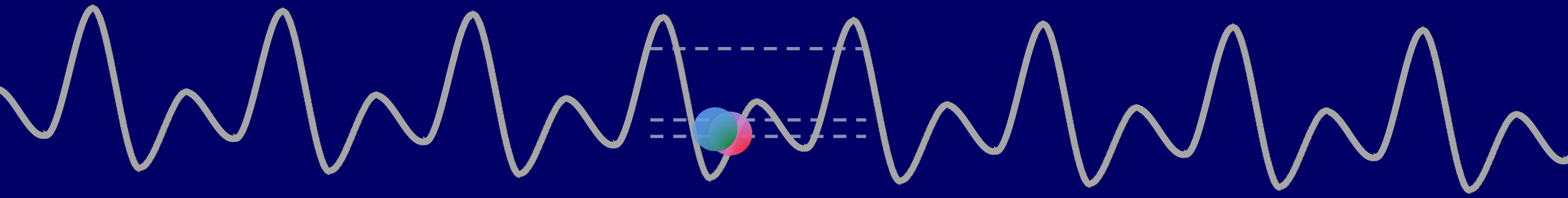




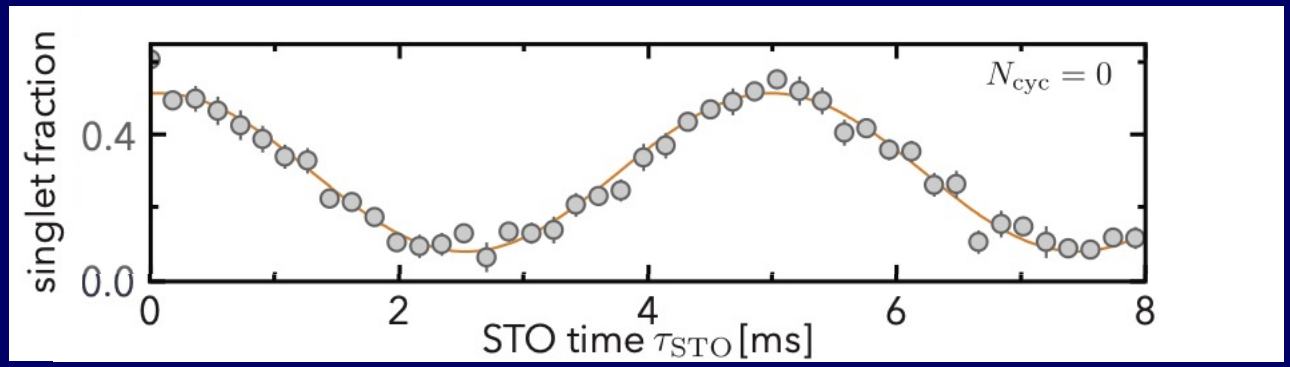
Single cycle fidelity over 50 cycles: 0.9957(4)

Z. Zhu, Y. Kiefer, S. Jele, M. Gächter, G. Bisson, K. Viebahn, and T. Esslinger arXiv:2409.02984v1

Splitting, recombining and measuring:



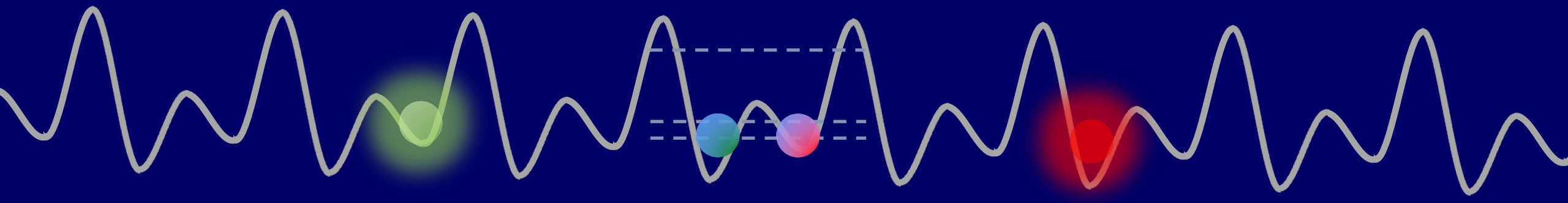
grad B



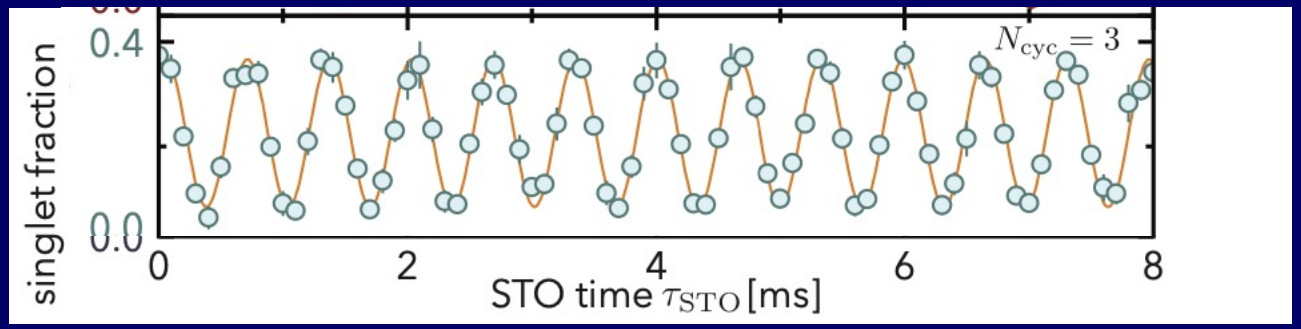
Singlet-triplet oscillations

Z. Zhu, Y. Kiefer, S. Jele, M. Gächter, G. Bisson, K. Viebahn, and T. Esslinger arXiv:2409.02984v1

Long distance singlet-triplet oscillations

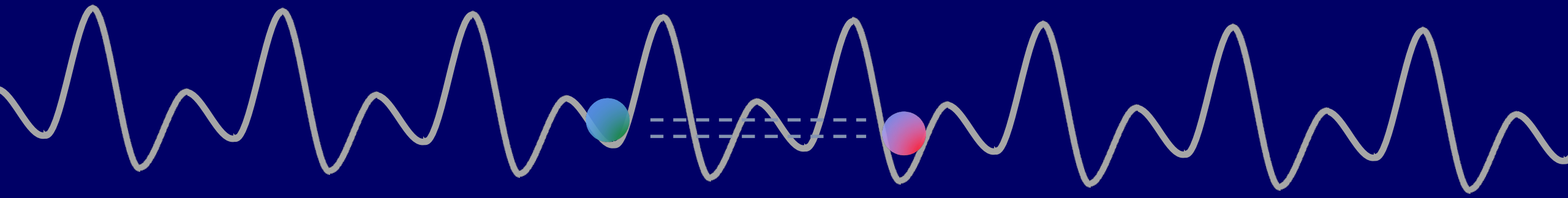


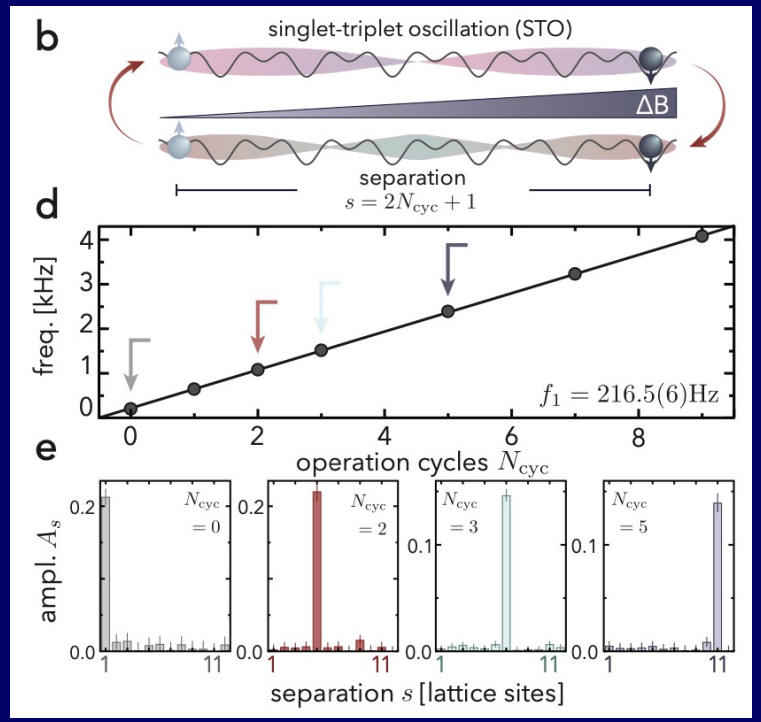
grad B



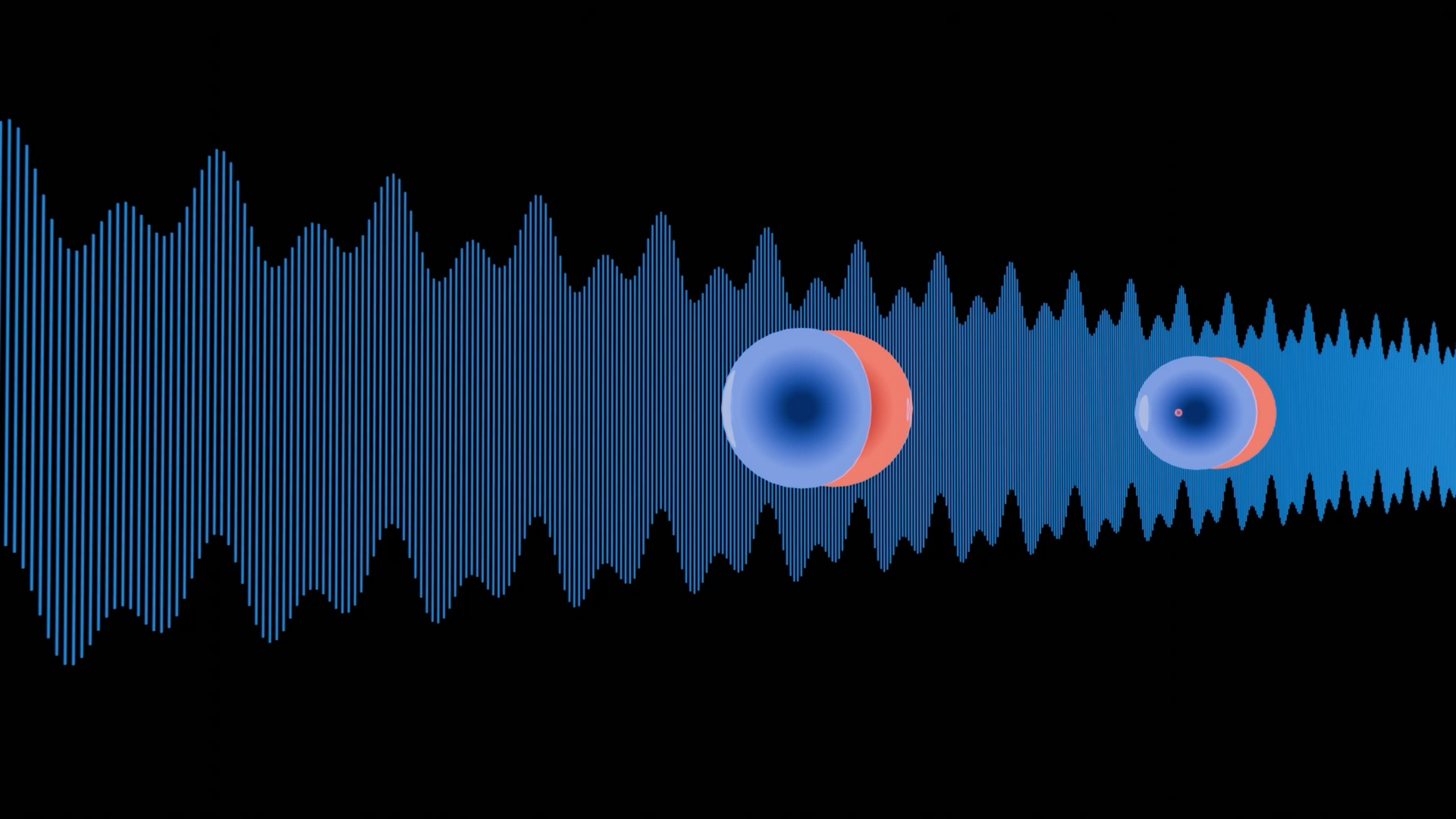
Z. Zhu, Y. Kiefer, S. Jele, M. Gächter, G. Bisson, K. Viebahn, and T. Esslinger arXiv:2409.02984v1

Transmission using SWAP gate

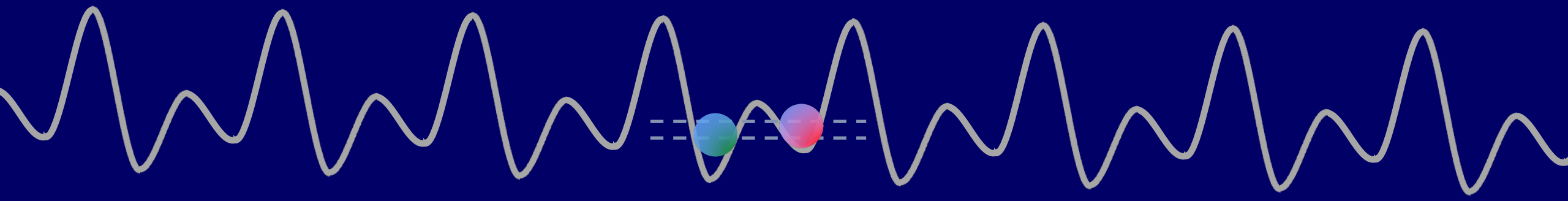


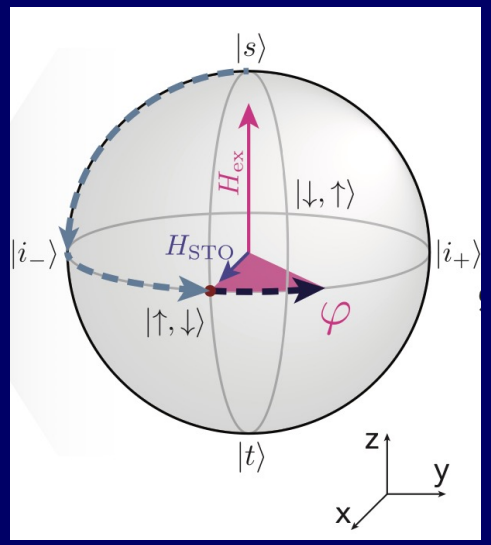


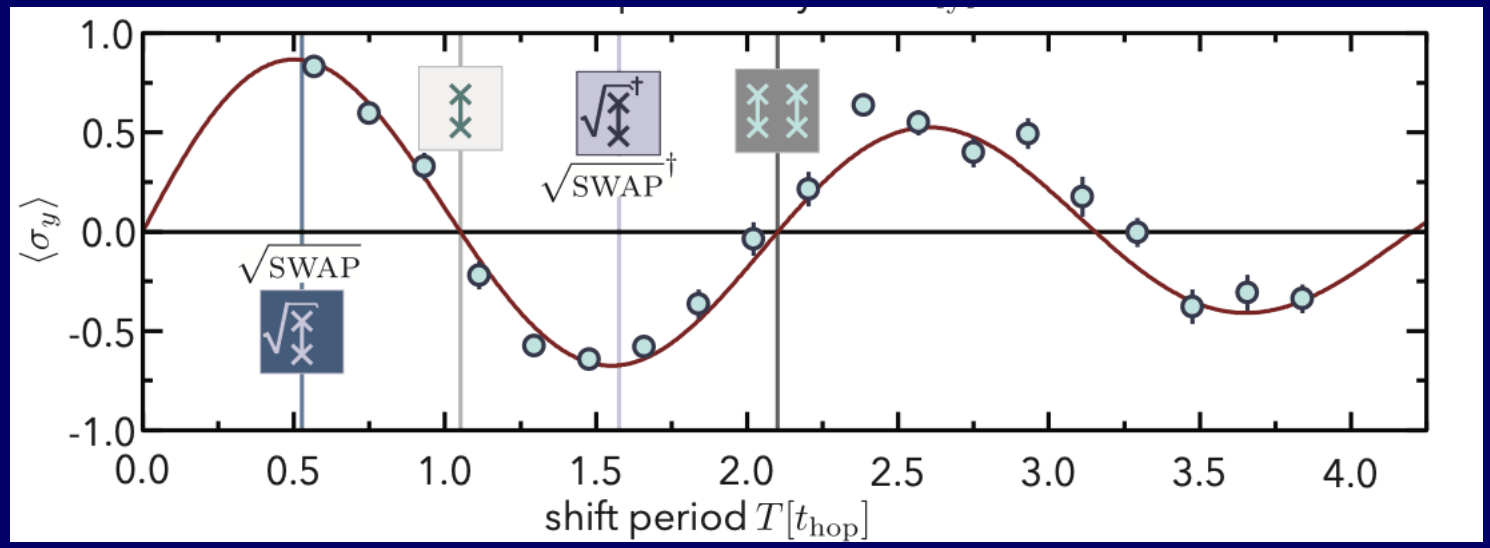
Z. Zhu, Y. Kiefer, S. Jele, M. Gächter, G. Bisson, K. Viebahn, and T. Esslinger arXiv:2409.02984v1



Variable SWAP

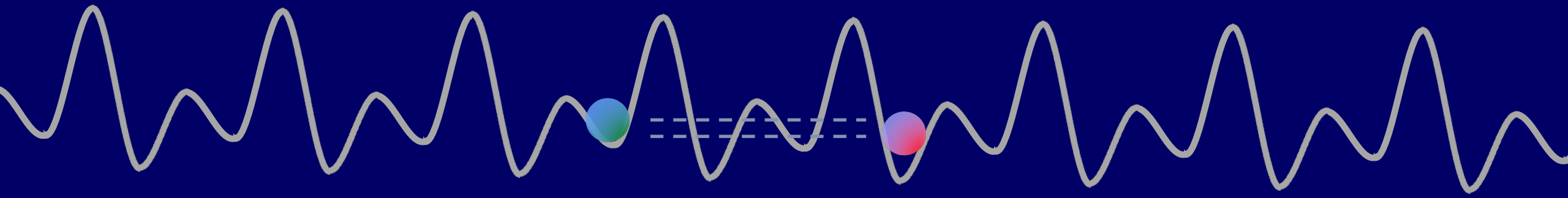


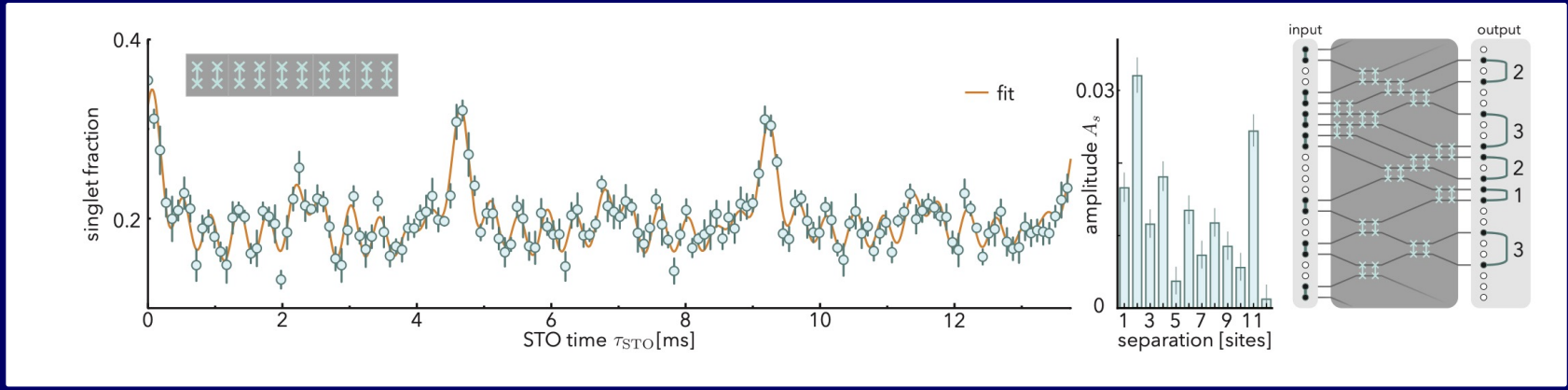




Z. Zhu, Y. Kiefer, S. Jele, M. Gächter, G. Bisson, K. Viebahn, and T. Esslinger arXiv:2409.02984v1

Reflection with SWAP^2 gate





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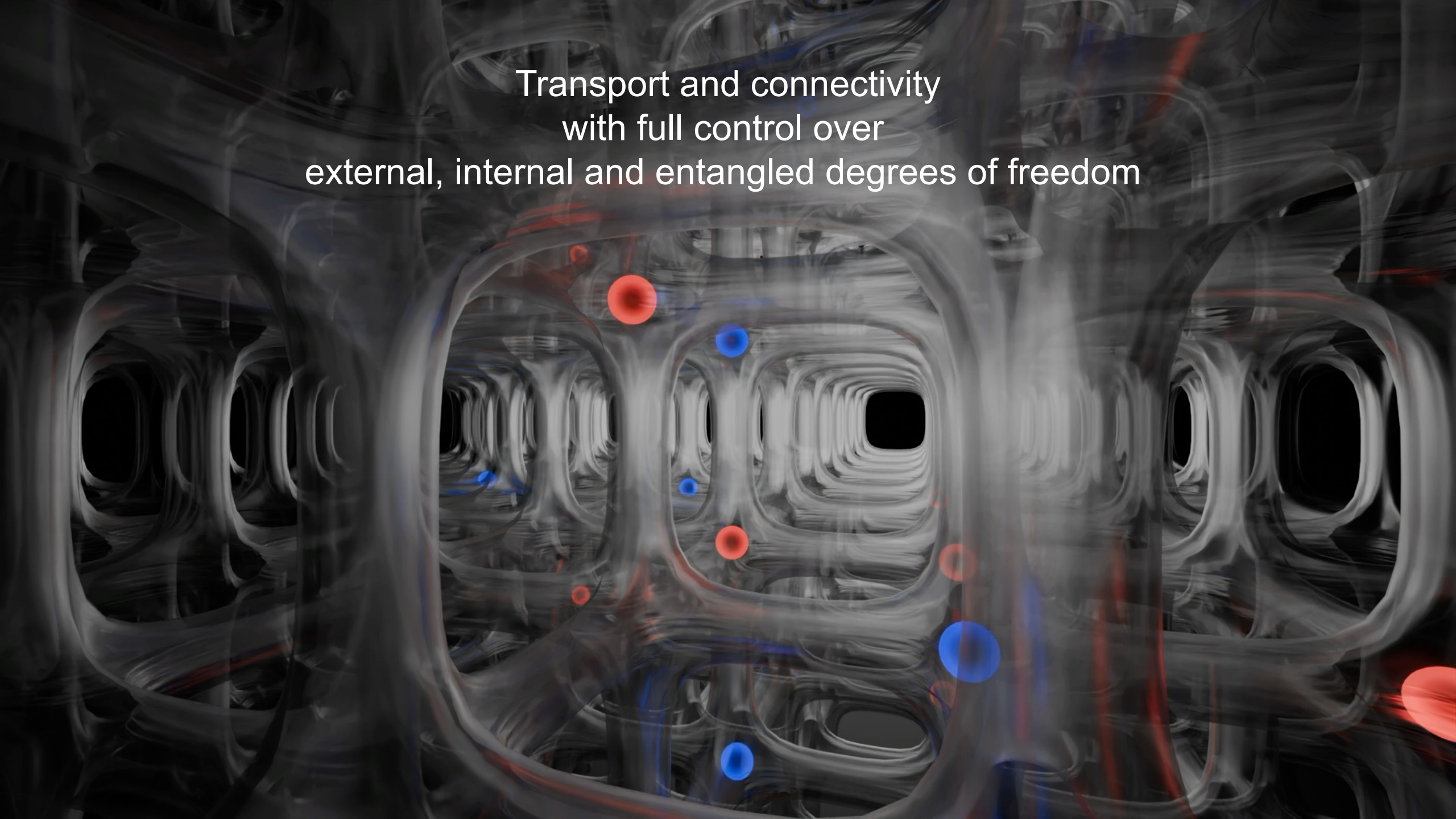
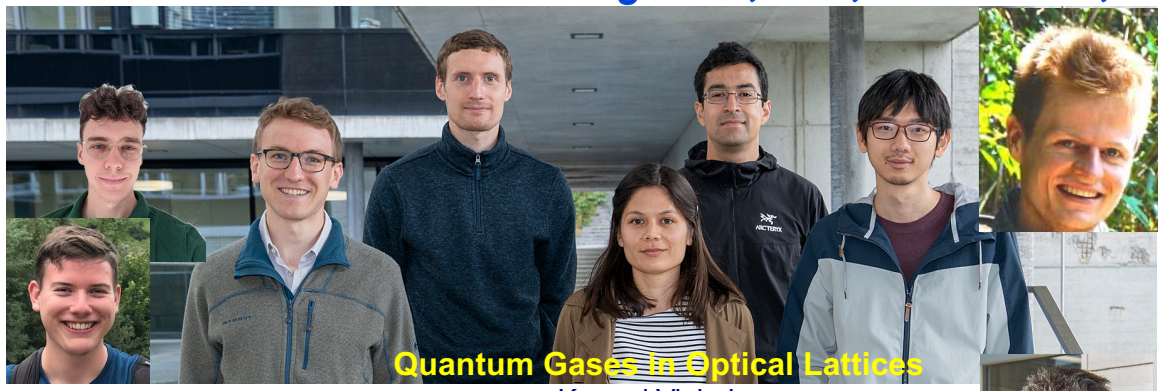

Transport and connectivity
with full control over
external, internal and entangled degrees of freedom

Thanks!

Funding: ETH, SNF, NCCR QSIT, EU Naquas, ERCadv TransQ, SNFadv



Quantum Gases in Optical Lattices

Konrad Viebahn
Zijie Zhu
Marius Gächter
Giacomo Bisson
Samuel Jele
Yann Kiefer
(Anne-Sophie Walter, Kilian Sandholzer
Joaquín Minguzzi)

Impact experiment

Tobias Donner
Justyna Stefaniak
Alexander Baumgärtner
Simon Hertlein
Gabriele Natale
David Baur

(Davide Dreon, Xiangliang Li)

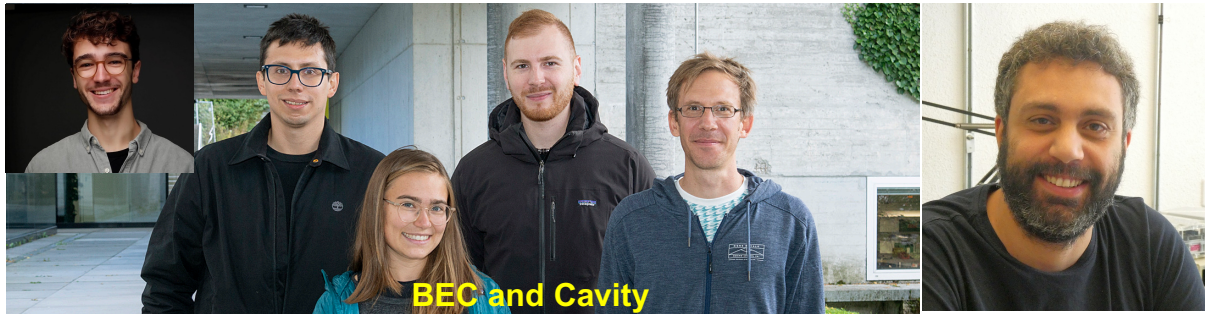
Electronics: Alexander Frank
Administration: Stefanie Ackermann

Lithium Transport

Philipp Fabritius
Jeffry Mohan
Mohsen Talebi
Meng-Zi (Myles) Huang
Simon Wili
(Samuel Häusler)
(Laura Corman)
(Martin Lebrat)

+ Jean-Philippe Brantut
Thierry Giamarchi
Anne-Maria Visuri
Pjotrs Grisins
Eugene Demler

Blender animations:
Mika Blackmore-Esslinger



BEC and Cavity

Tobias Donner
Rodrigo Rosa-Medina
Fabian Finger
Nicola Reiter
Jacob Fricke
Panagiotis Christodoulou

(Francesco Ferri, Nishant Dogra,
Katrin Kröger, Manuele Landini)