Quantum gases in Optical Lattices
Lecture #2

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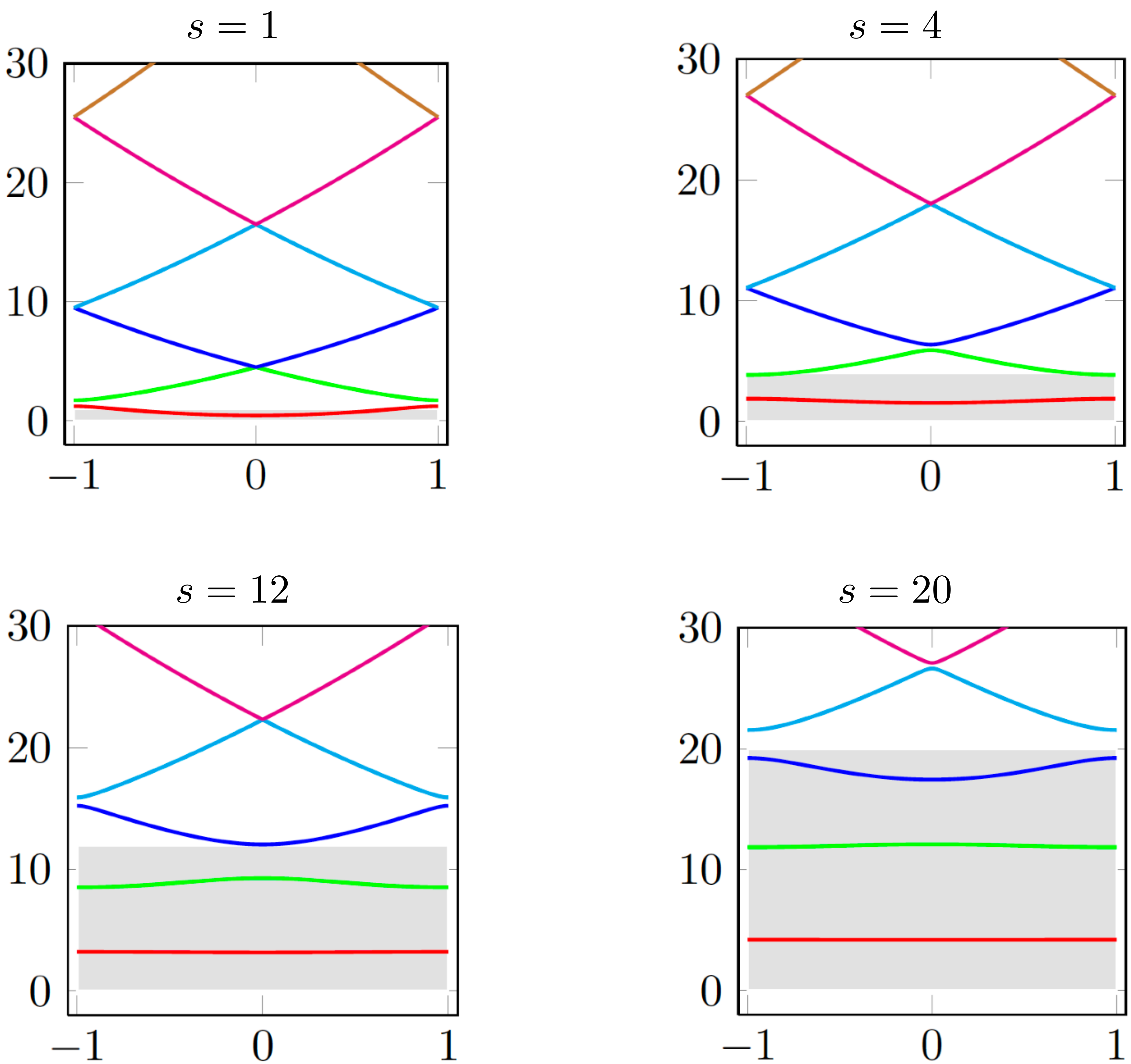
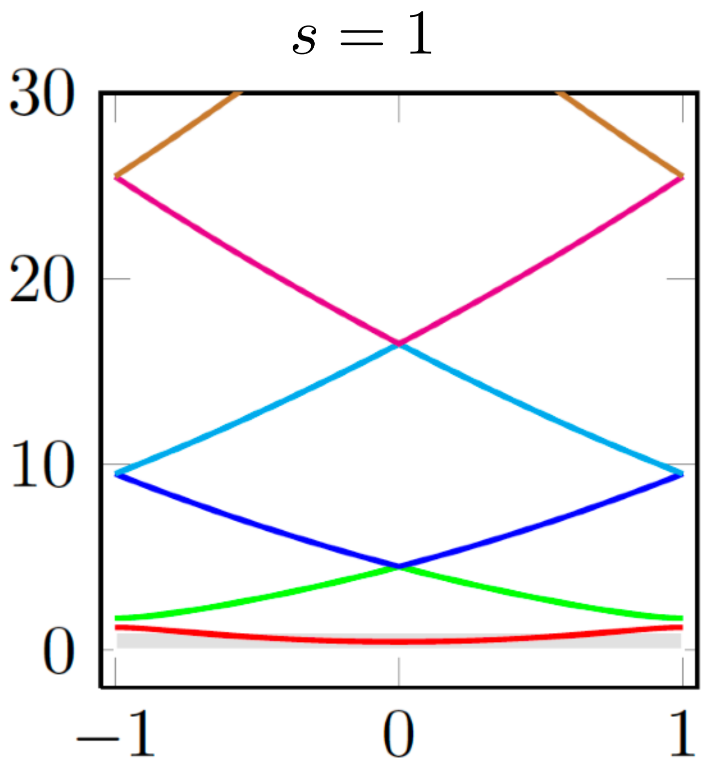
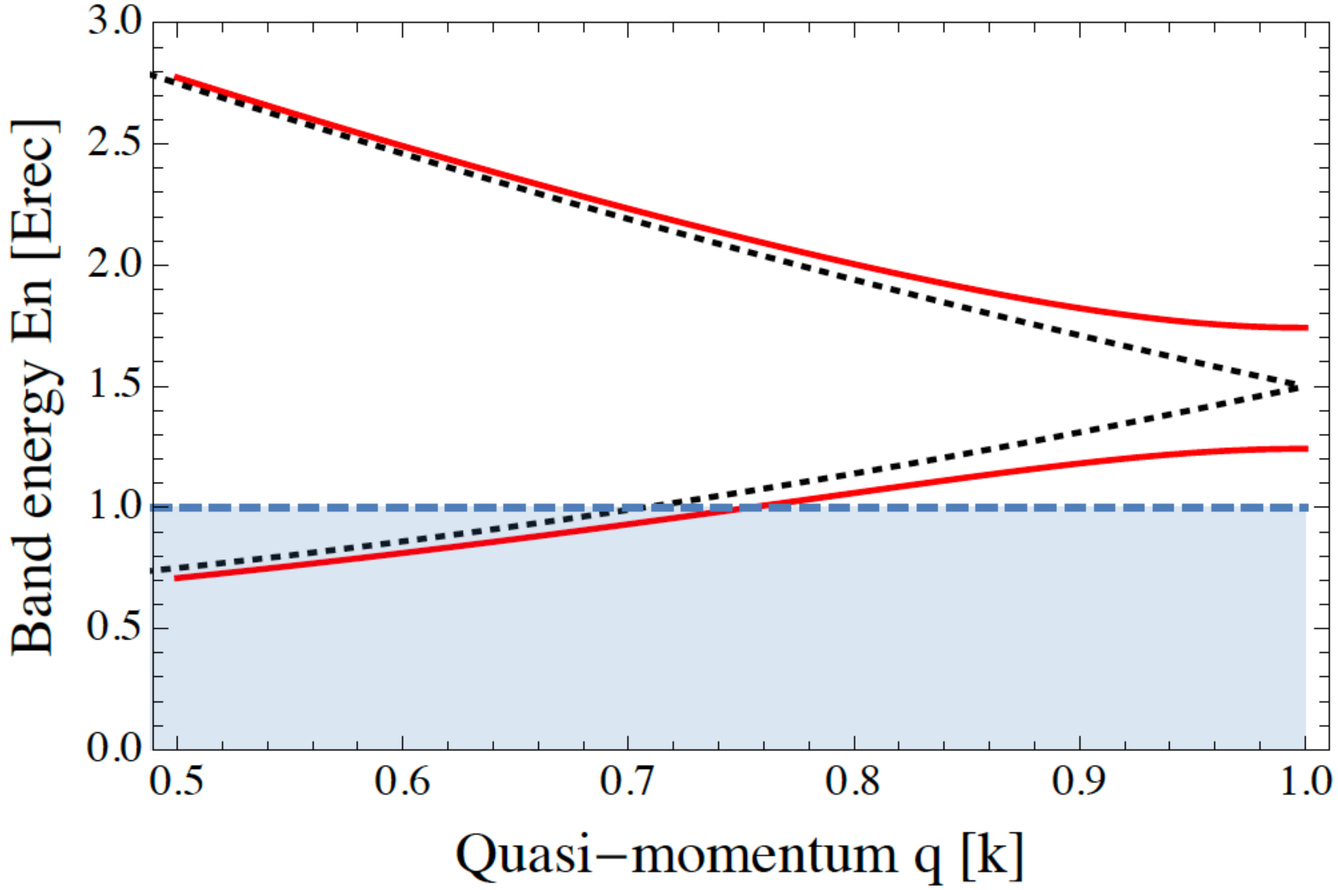
Band structure in a 1D lattice



Crédit: H. Perrin

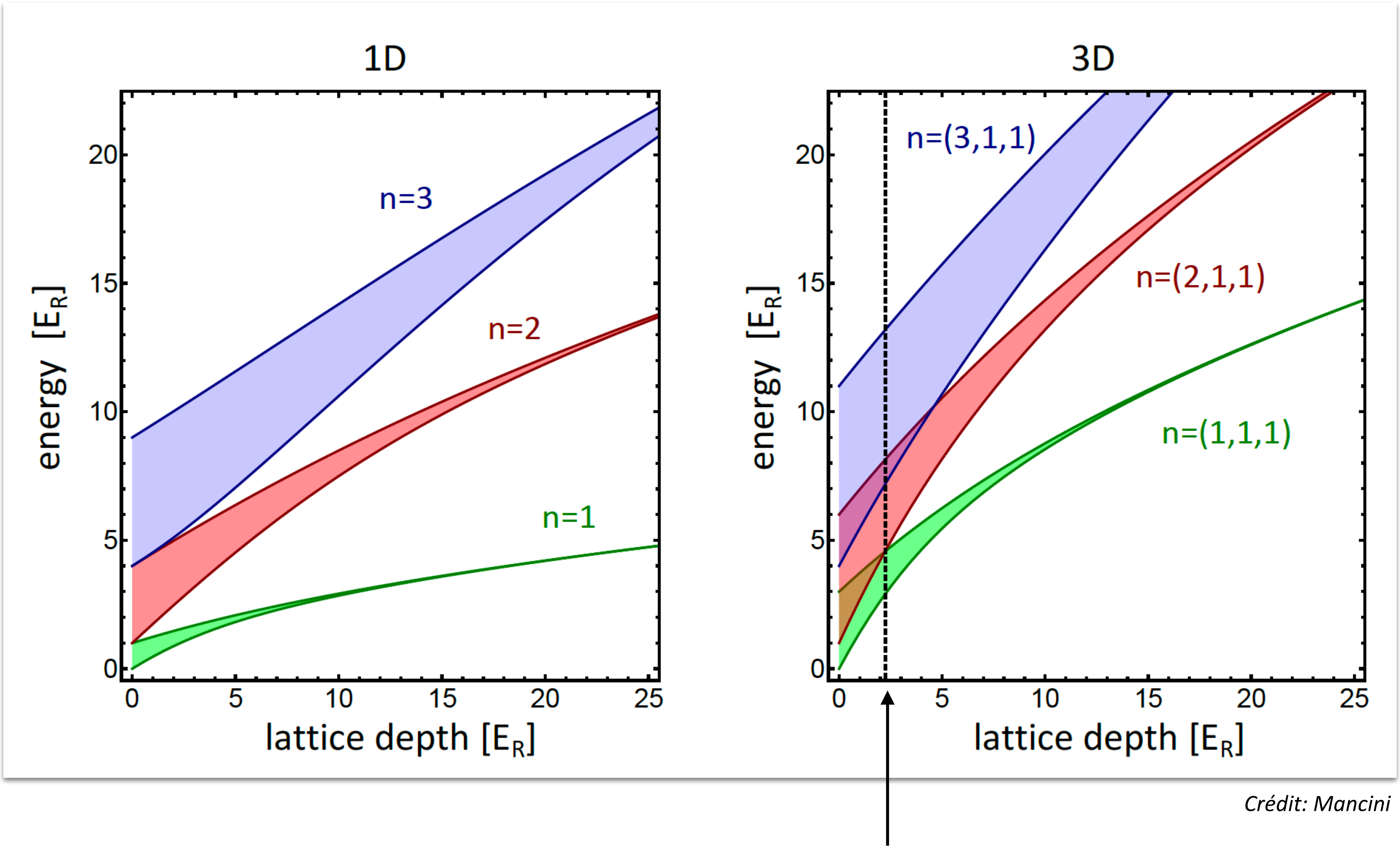
Band gaps in square lattices





Crédit: H. Perrin

Band gaps in square lattices

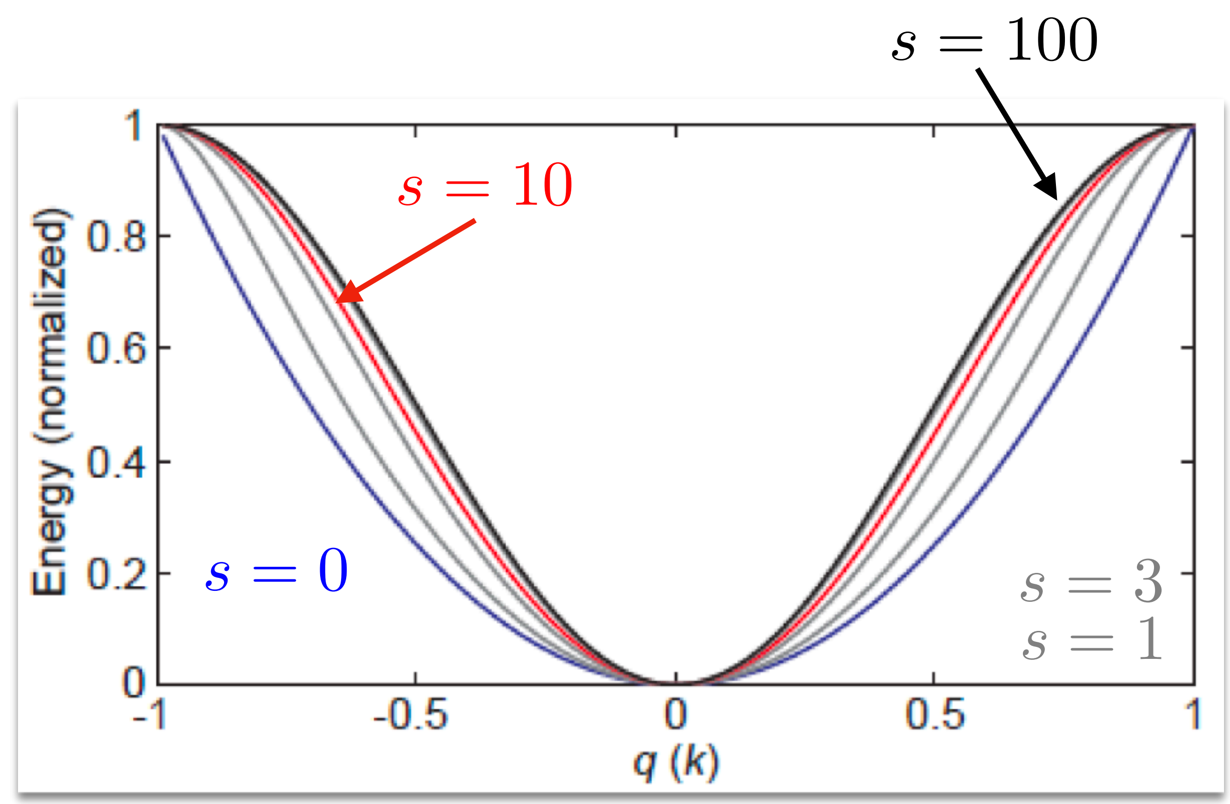


Crédit: Mancini

$V_0 \simeq 2.2 E_R$

Lowest-energy band

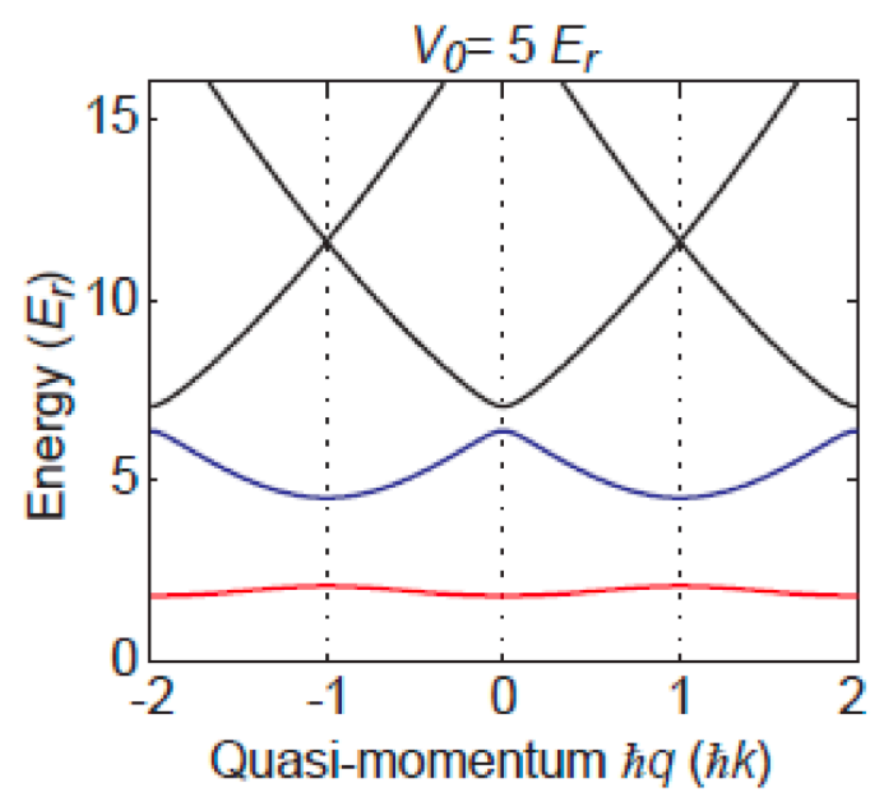
Normalized and shifted lowest-energy bands.



lowest-energy band dispersion smoothly changes from parabolic to sinusoidal:

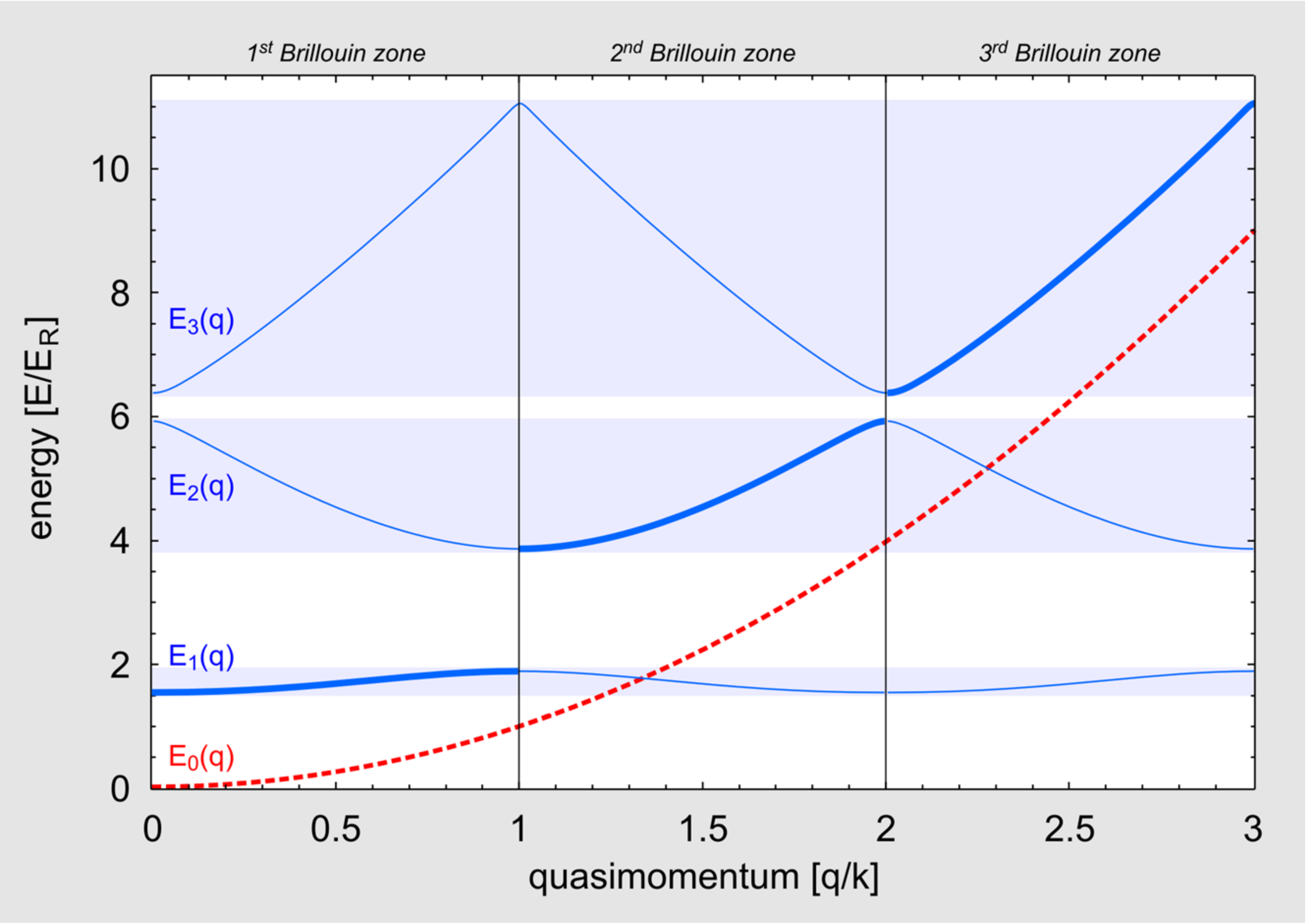
$$E(q) - E_0 \simeq 4J\sin(qa/2)^2$$

Tight-binding regime (*lectures #3, #4*)



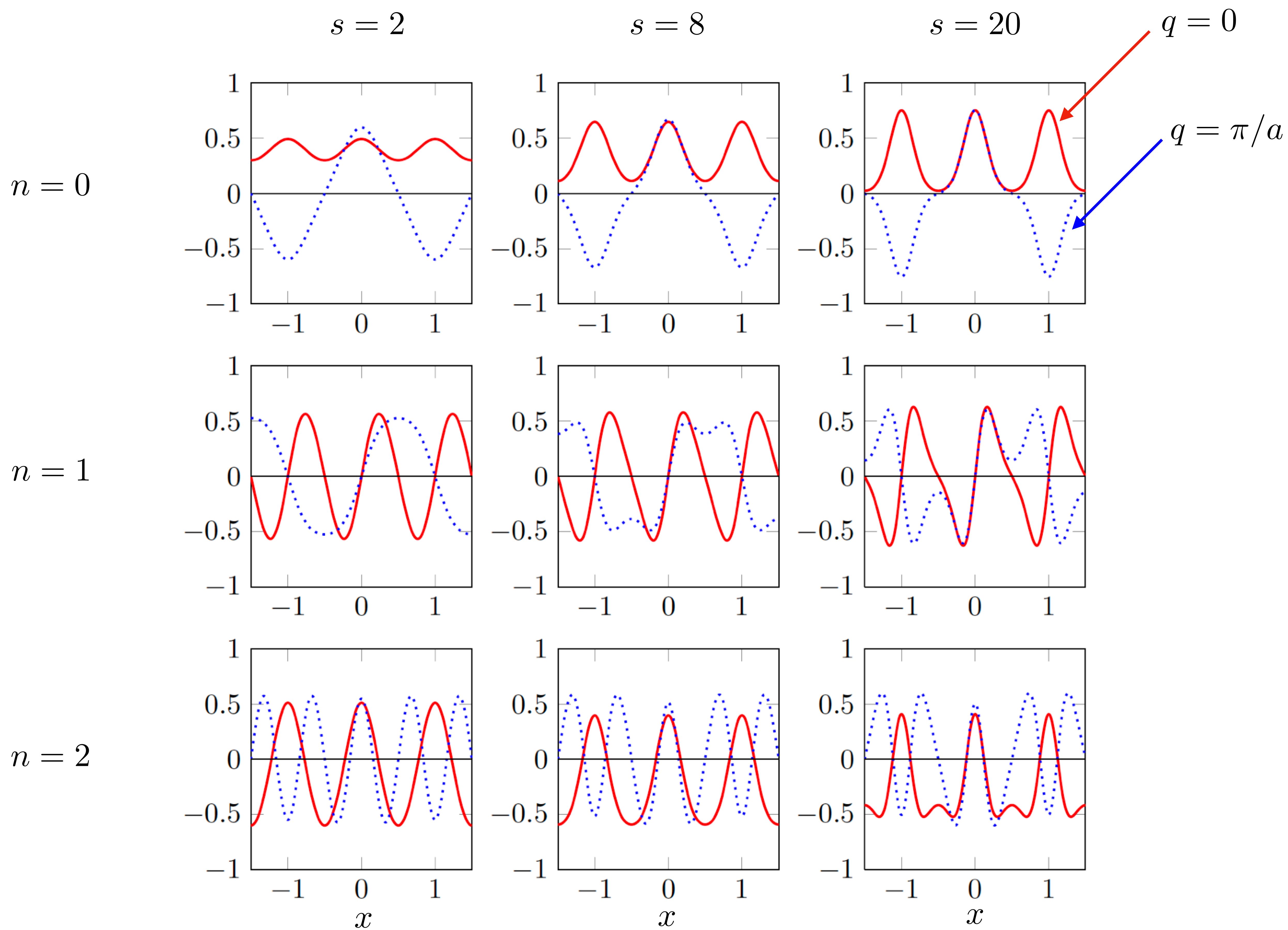
$s \gtrsim 5$: energy bandwidth << energy bandgap

Band structure: summary



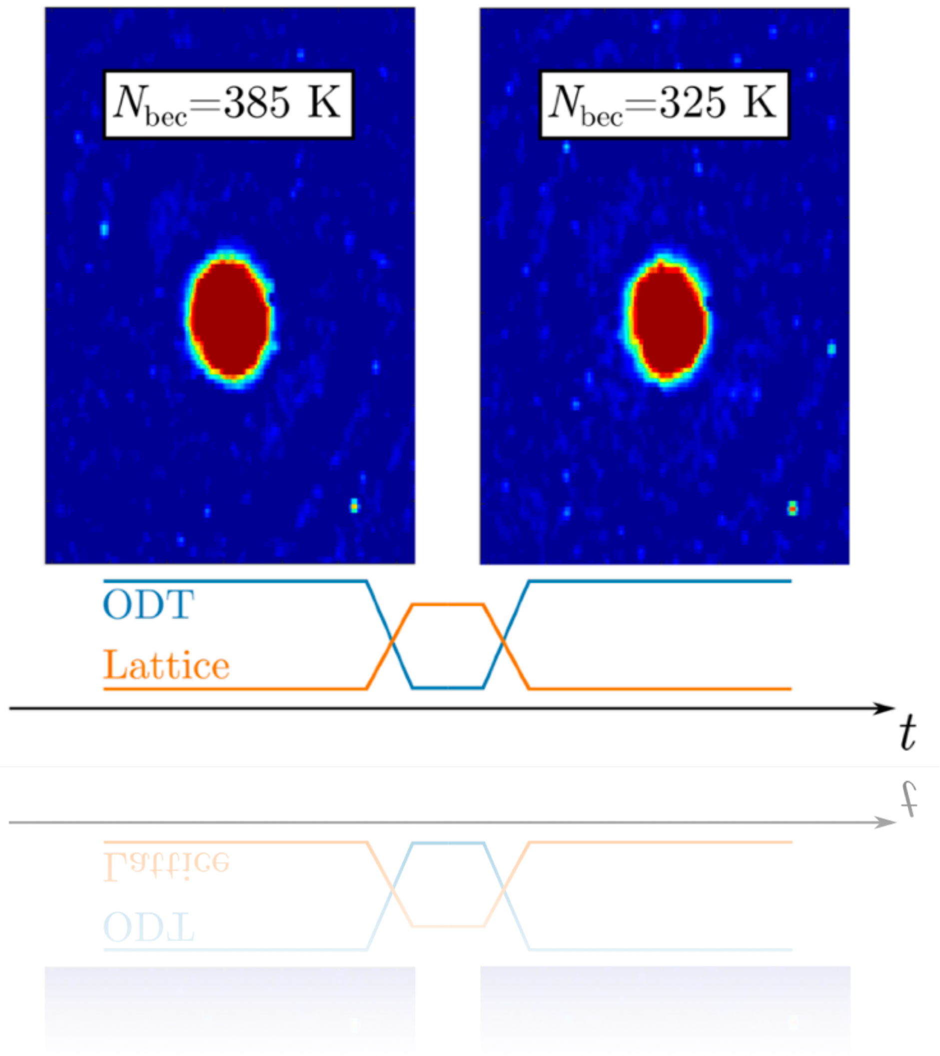
Crédit: Fallani

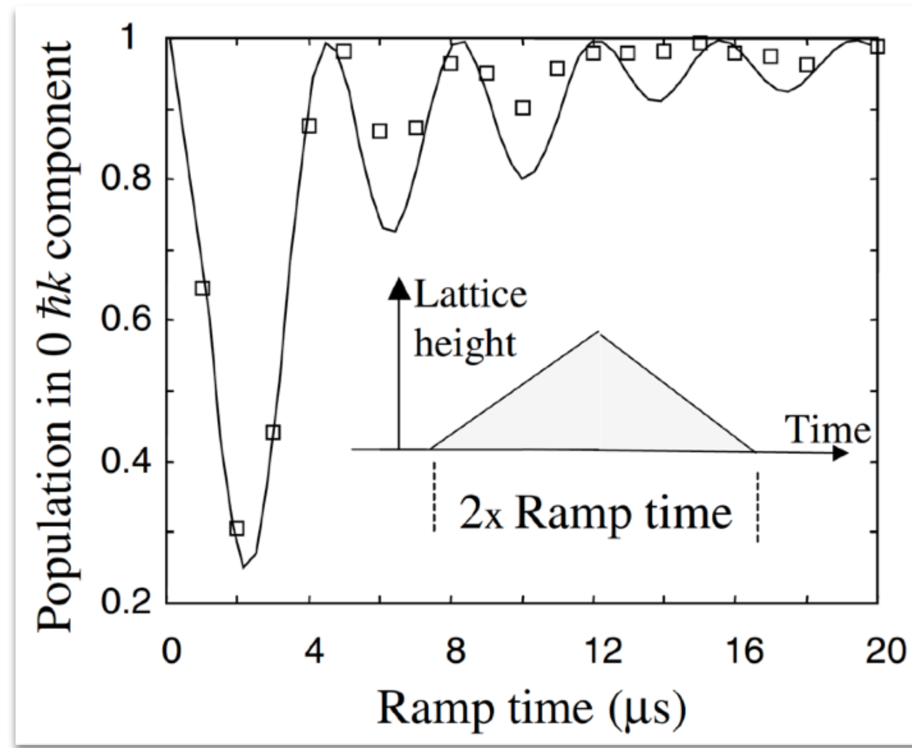
Bloch wave-functions



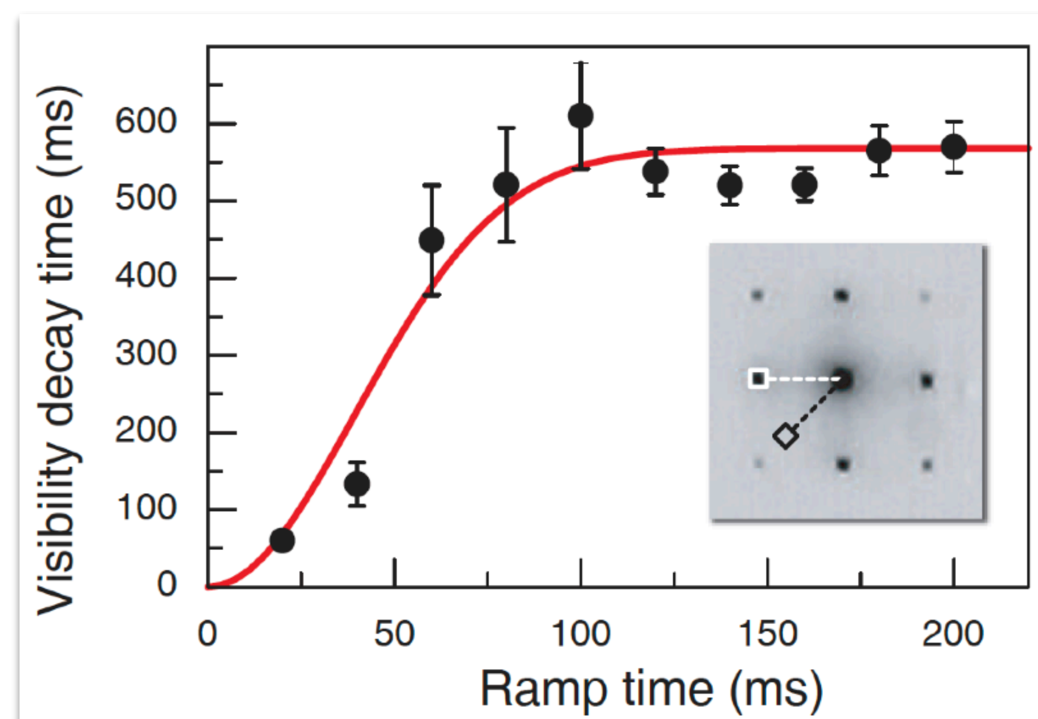
Crédit: Dalibard

Adiabatic loading in the lattice





Denschlag et al. J. Phys. B: At. Mol. Opt. Phys. ***35*** *(2002)*



Gericke et al. J. Mod. Phys. ***54*** *735 (2006)*

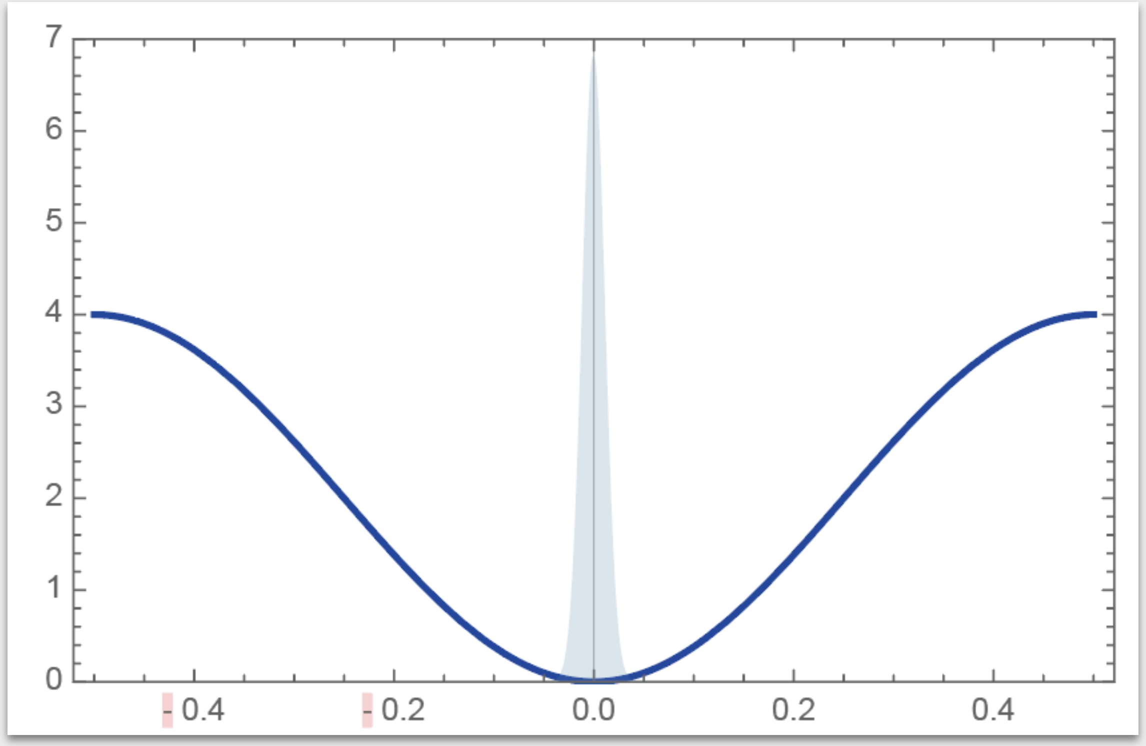
Difficult to characterise precisely in experiment due to (small) atom losses being present

<u>NB:</u> condition for adiabatic loading in the presence of interaction non-trivial problem (see later)

Carcy et al. Phys. Rev. Lett. ***126*** *045301 (2021)*

Non-interacting lattice bosons

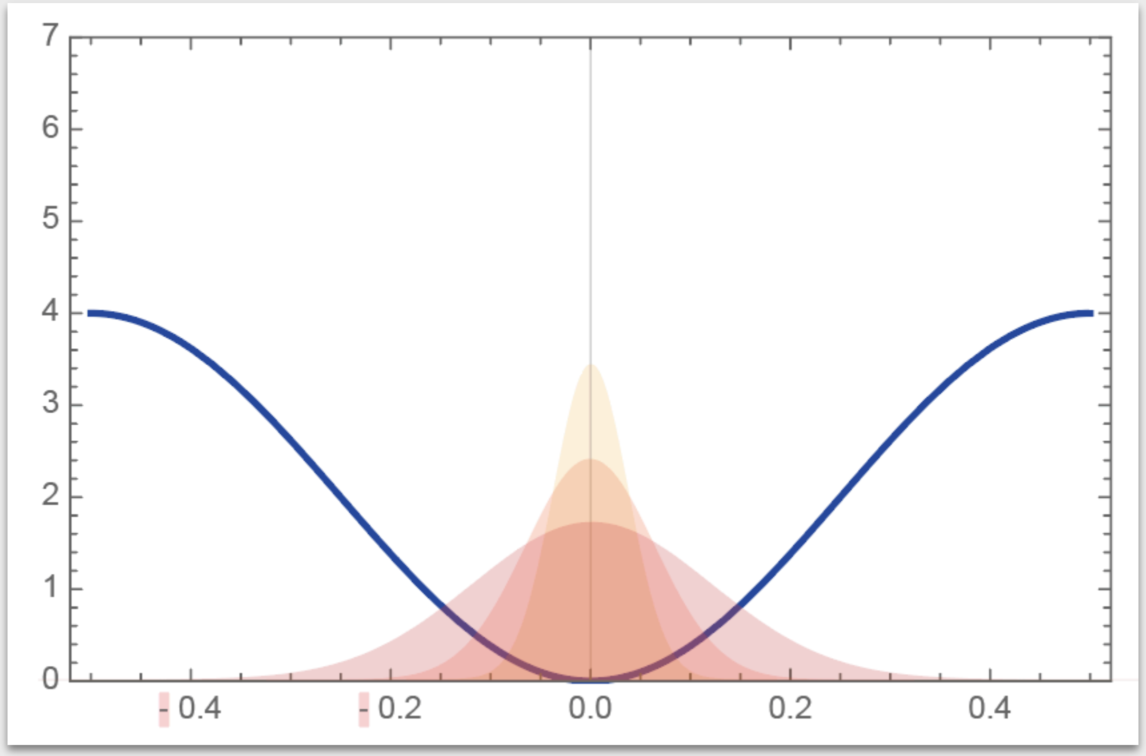
Bose-Einstein condensate at $q = 0$



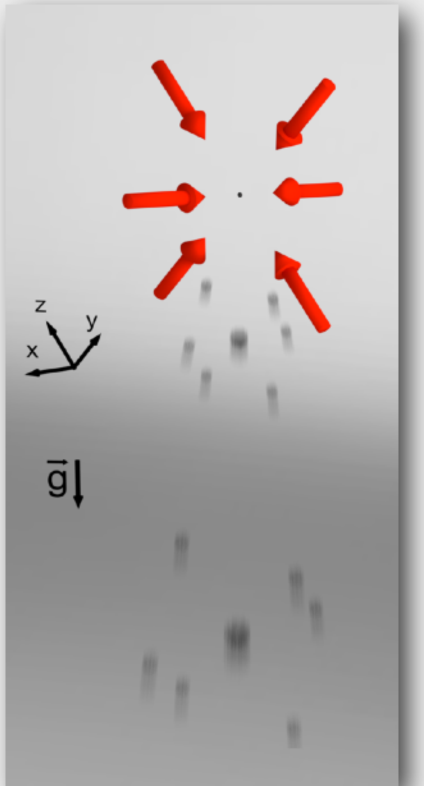
$$|\Psi_0\rangle = \frac{1}{\sqrt{N!}}[a^\dagger(q=0)]^N|0\rangle$$

Similar properties as BEC in a box or harmonic trap (coherent state)

Thermal cloud $k_B T \ll$ energy gap

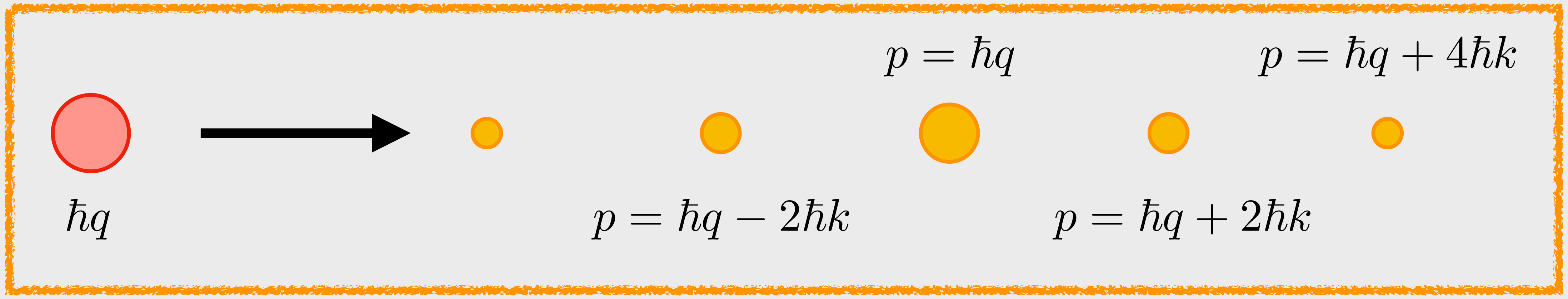


Time-of-flight imaging

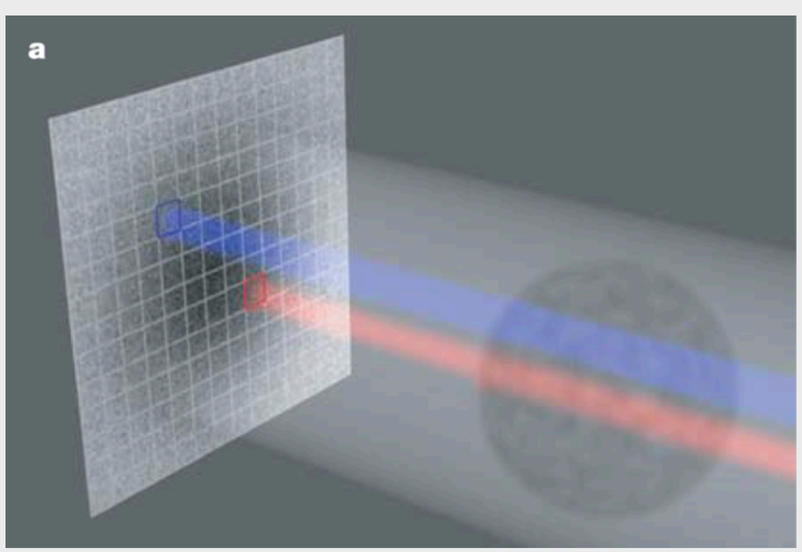


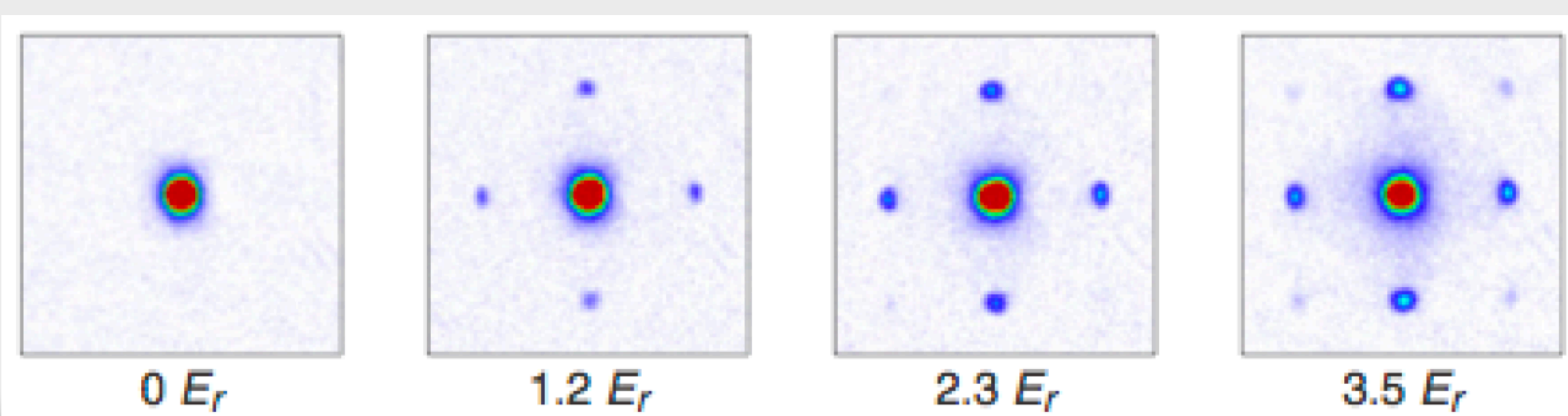
Sudden switch off the trap: projection from Bloch waves onto plane wave basis

$$\hbar q \rightarrow p = \hbar q \pm 2j\hbar k$$



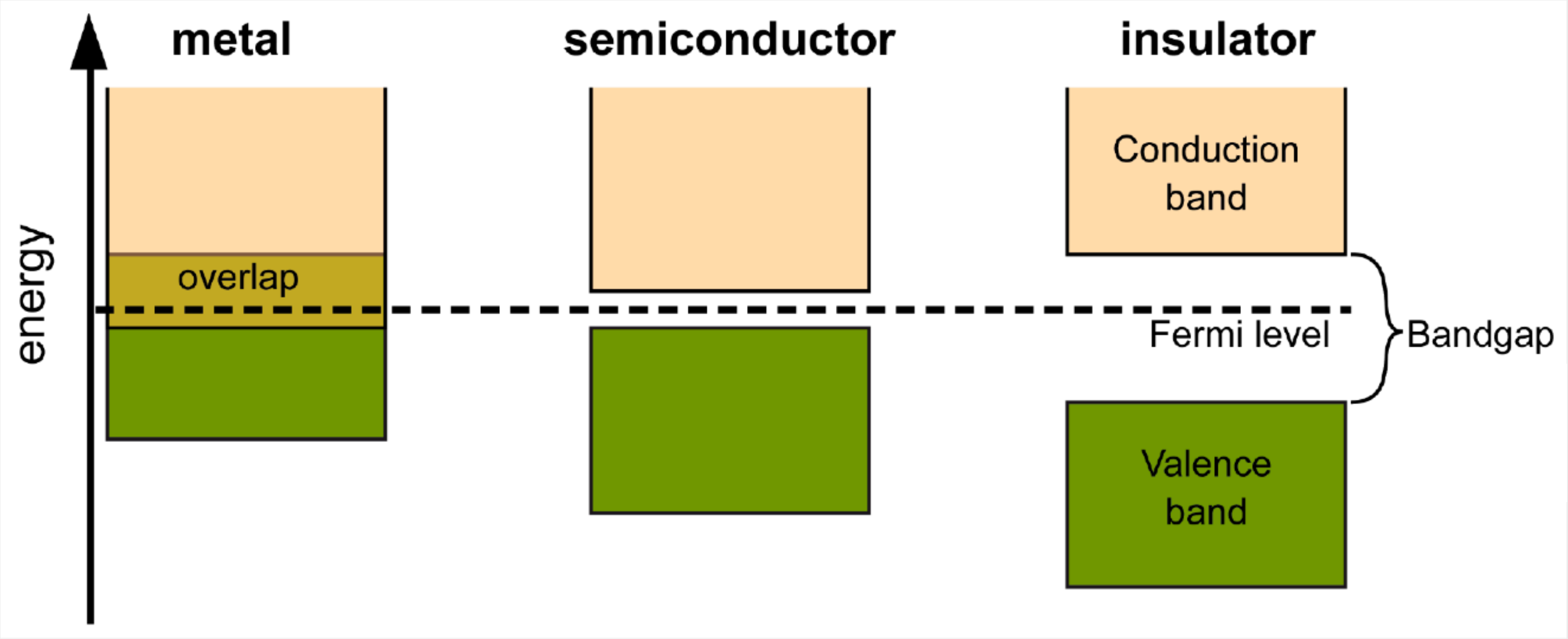
BEC: expansion of a phase-coherent matter wave from a periodic structure *(optical analog)*





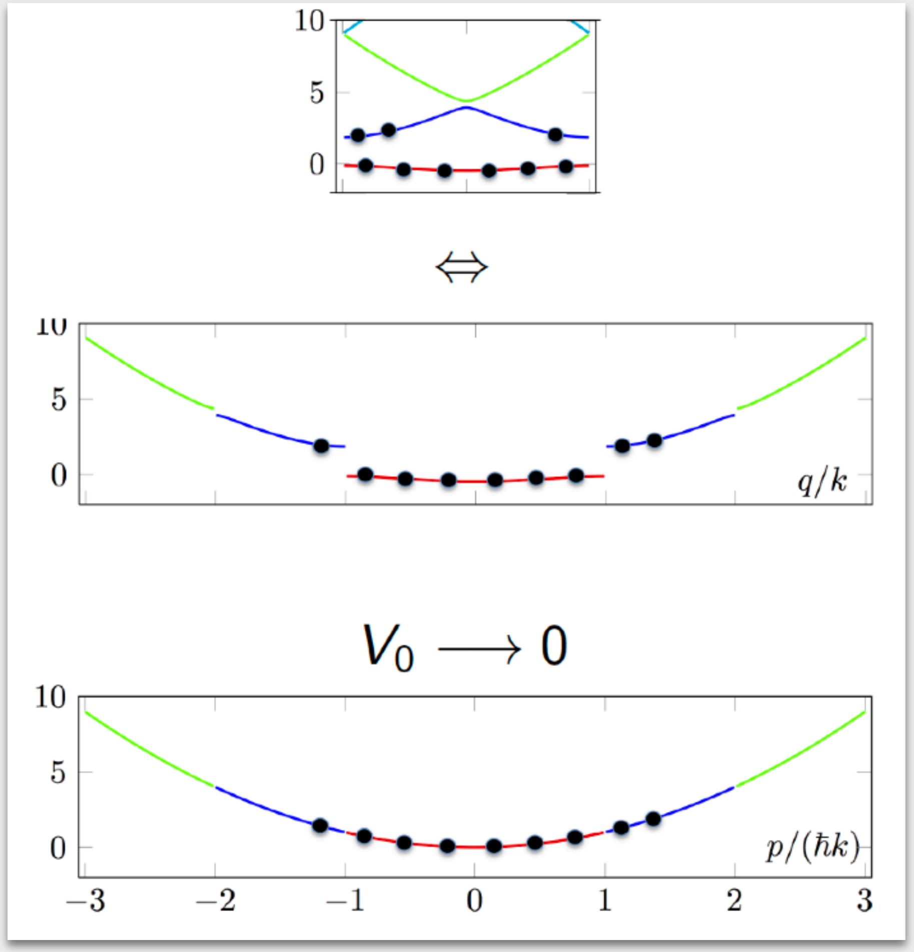
Greiner et al. Nature (2002)

Non-interacting lattice fermions



How to obtain the population of the different bands?

Band mapping technique

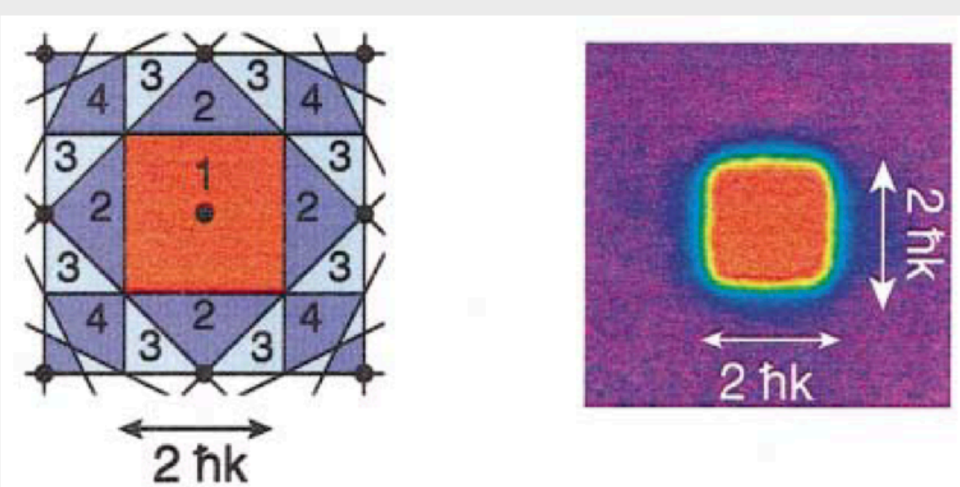


Crédits: H. Perrin

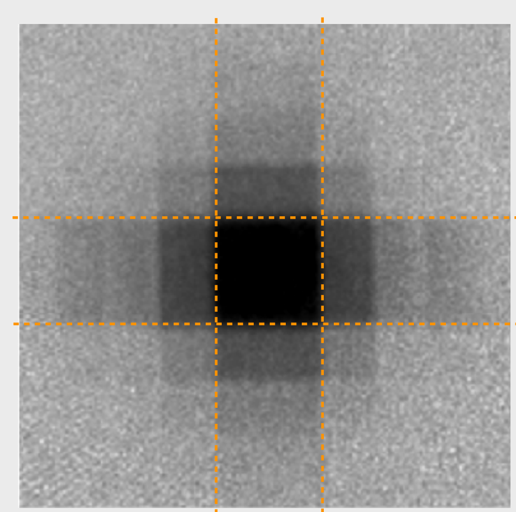
Map band population onto momentum states: adiabatic closing of the lattice bands
(time scale for decreasing lattice amplitude longer than energy gap between lowest bands)

NB: fast enough to avoid interaction (when present) mixing momentum components

Incoherent Bose gas in lowest-energy band

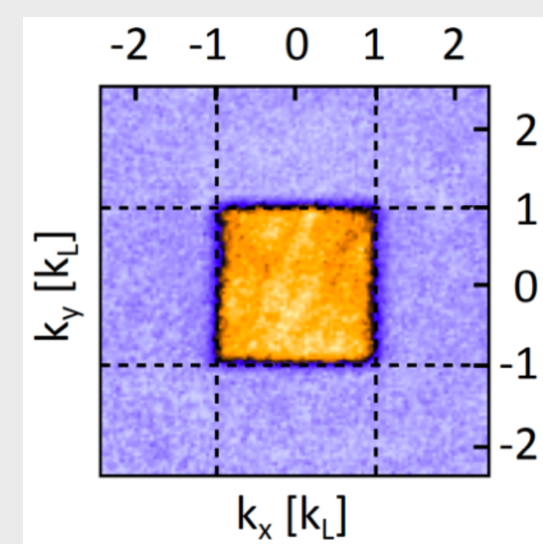


Higher bands populated



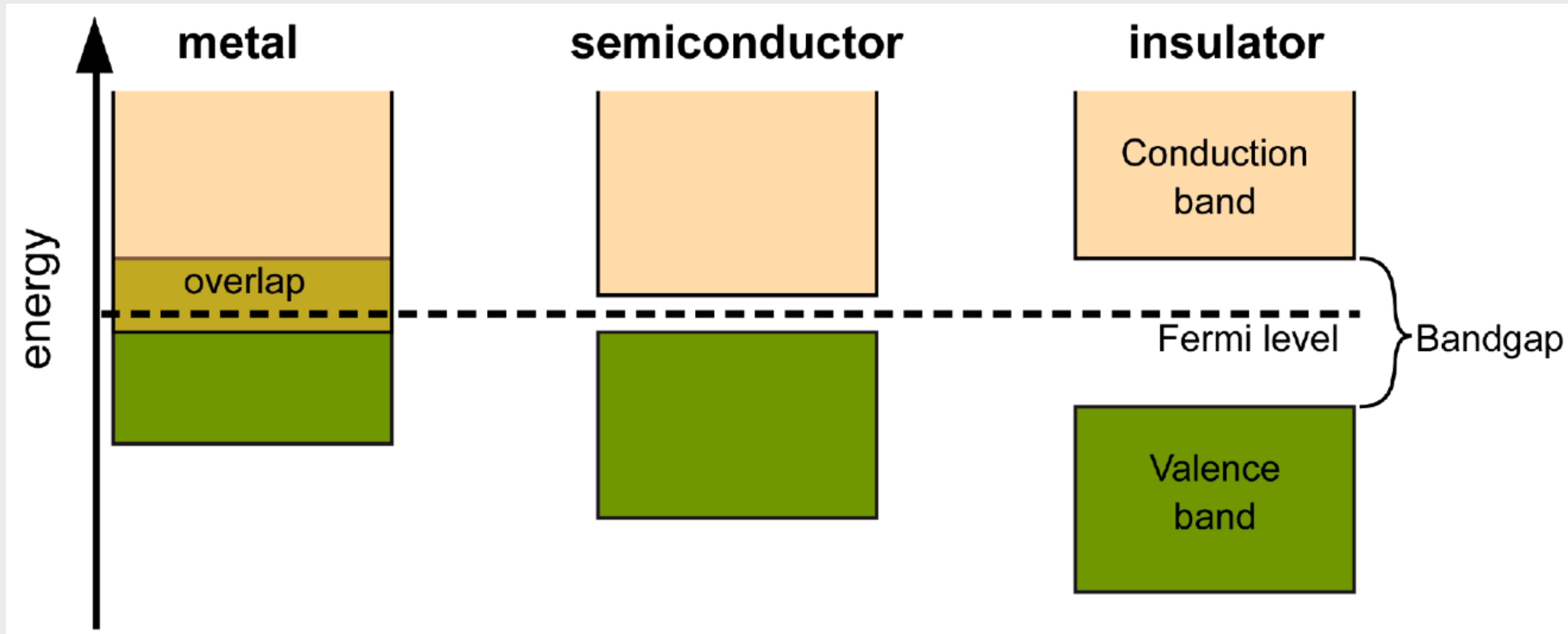
*Greiner et al. PRL **87** (2001)*

Fermions

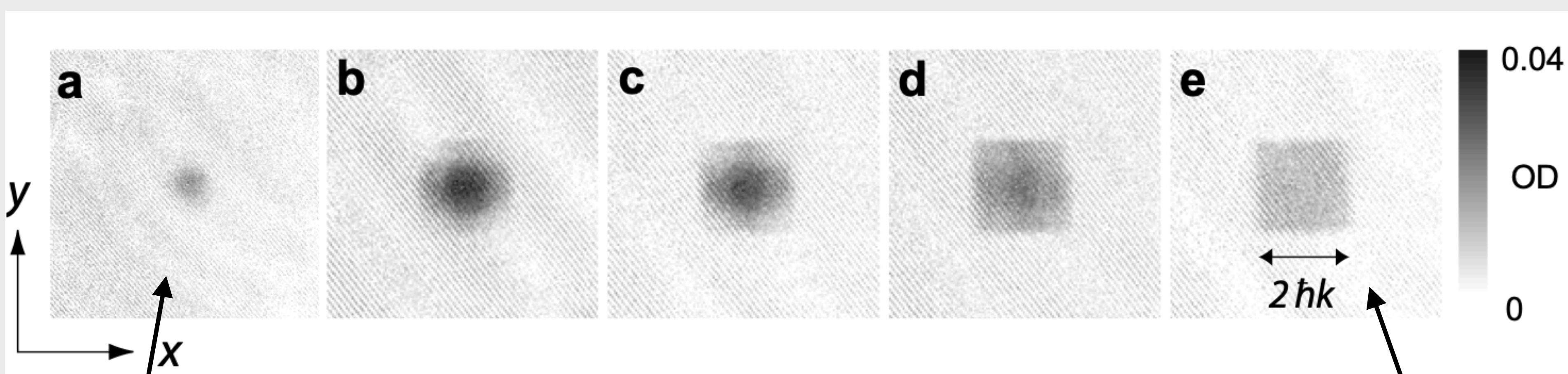


Mancini @LENS - Florence (2015)

Non-interacting lattice fermions

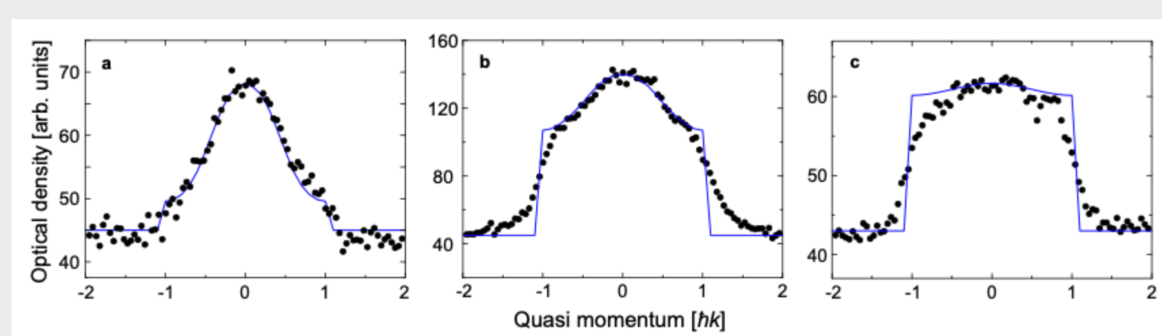


*Kohl et al. PRL **94** 080403 (2005)*



Normal state

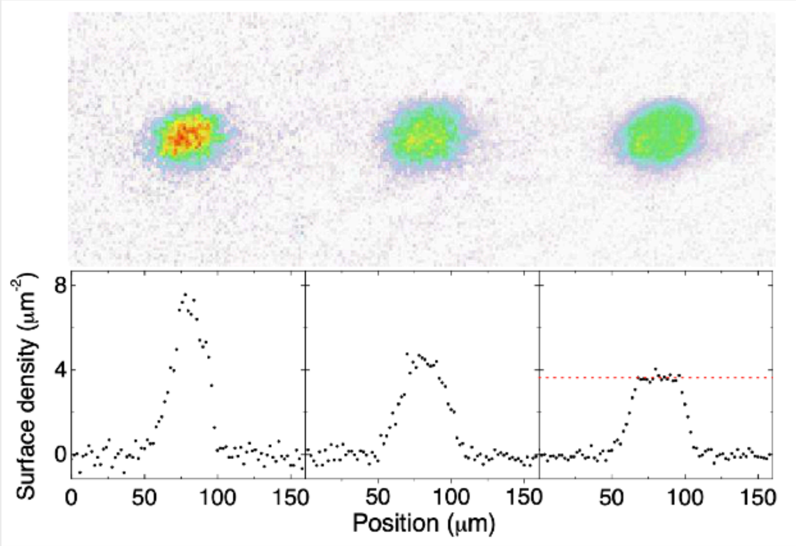
Band insulator



In-situ quantum gas microscopes

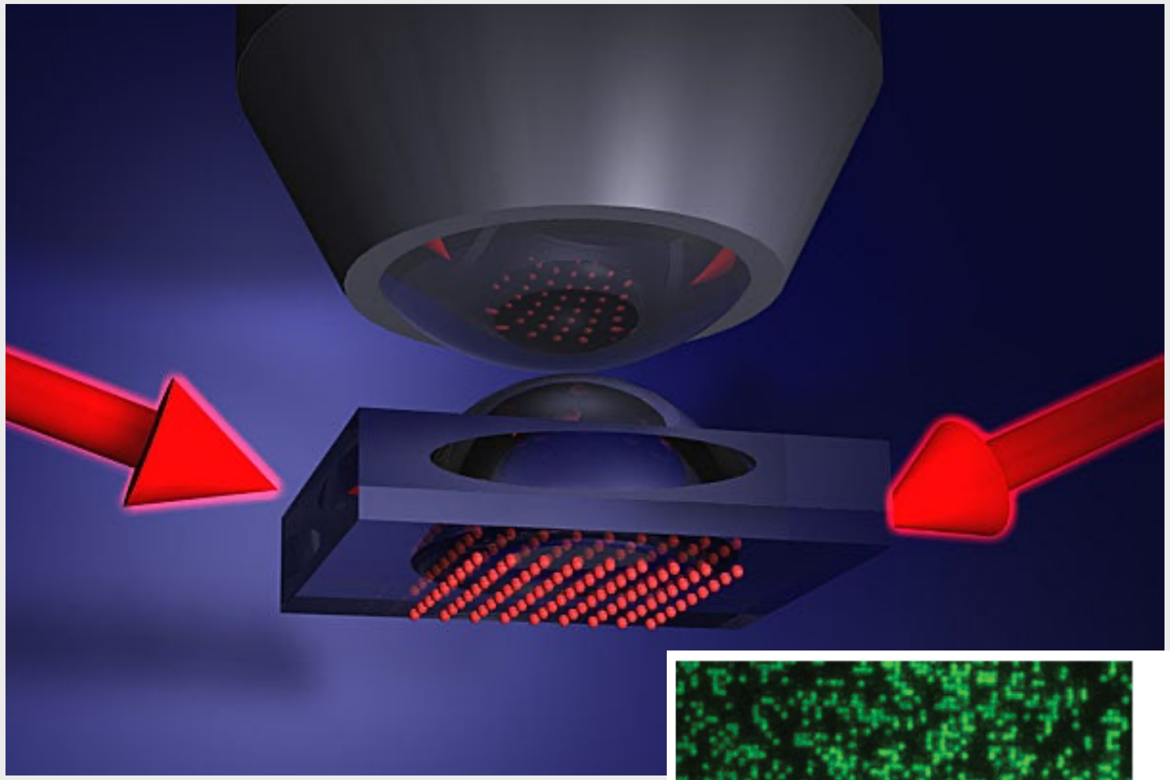
Measurement of the atomic density in the lattice

(no single-atom-resolved or single-site-resolved)

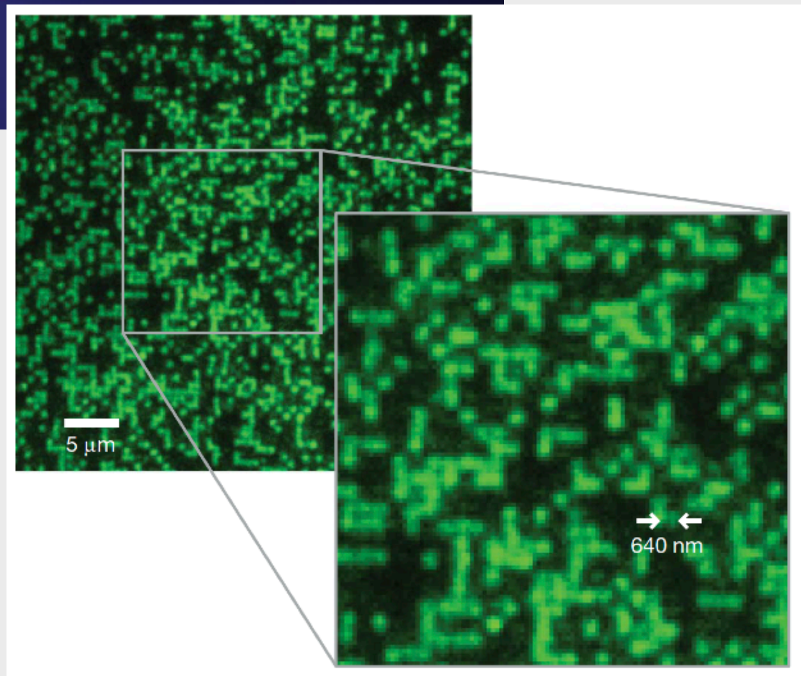


Gemelke et al. Nature ***460****, 995 (2009)*

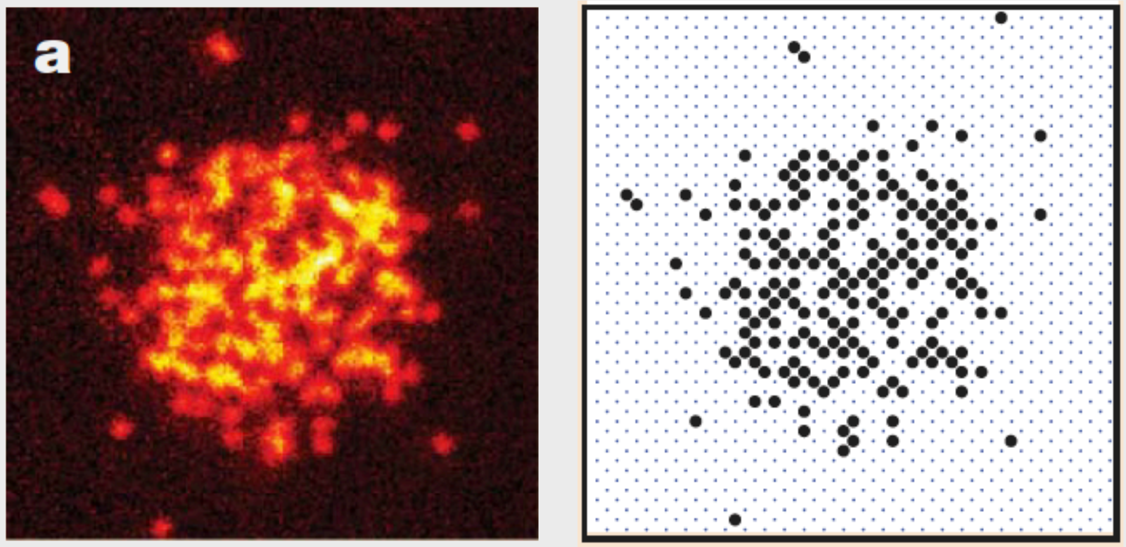
Quantum gas microscopes



Bakr et al. Nature ***465****, 74 (2009)*

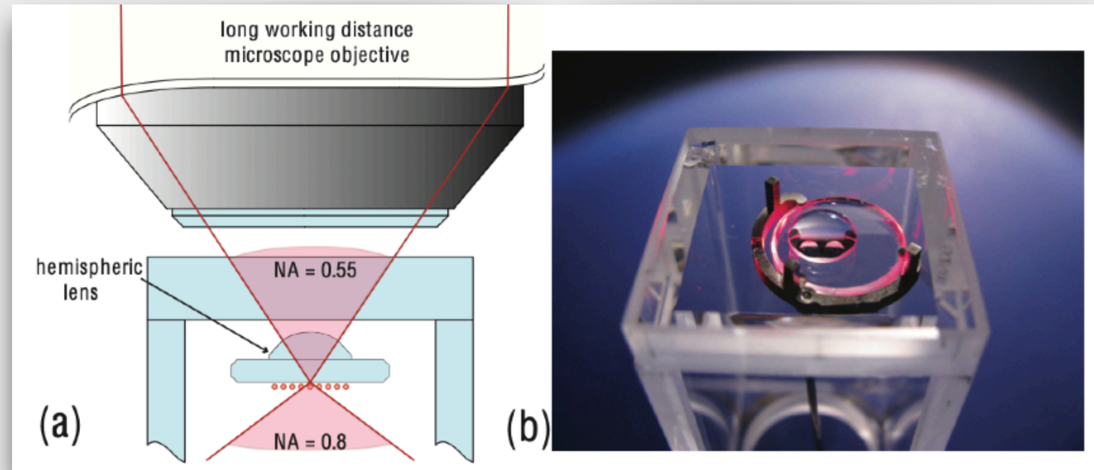


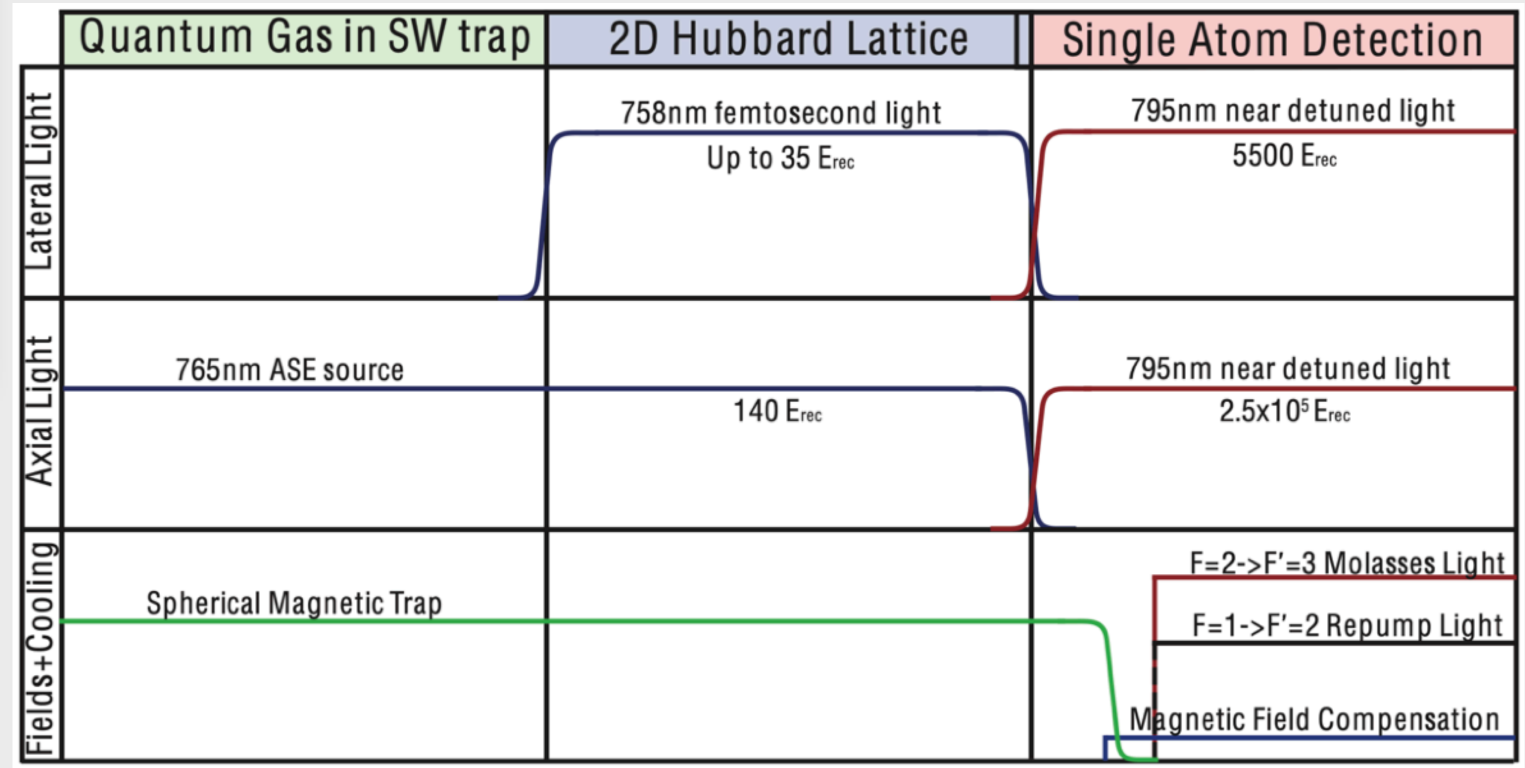
2D lattice BEC



Sherson et al. Nature ***467****, 68 (2010)*

Quantum gas microscopes





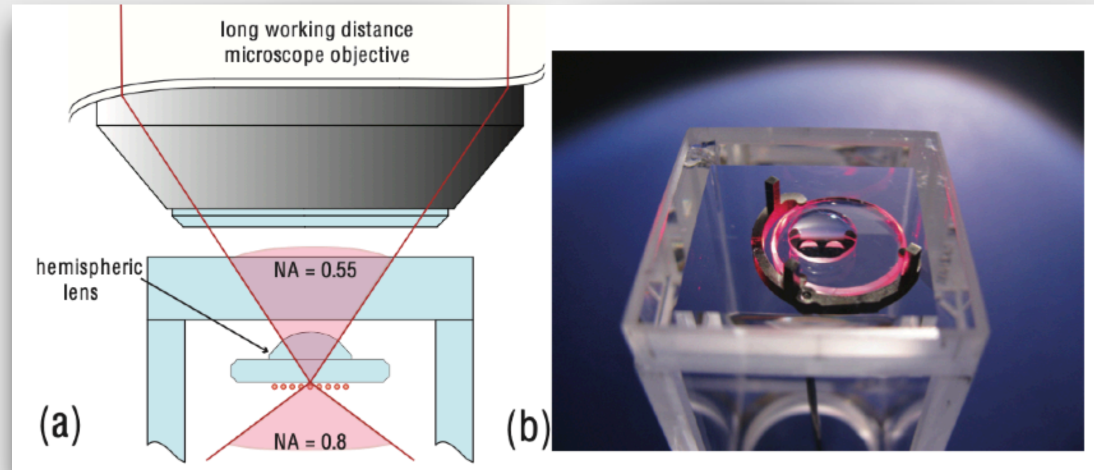
Gillen PhD thesis (Greiner's group 2009)

Physics lattice
10-100 ms

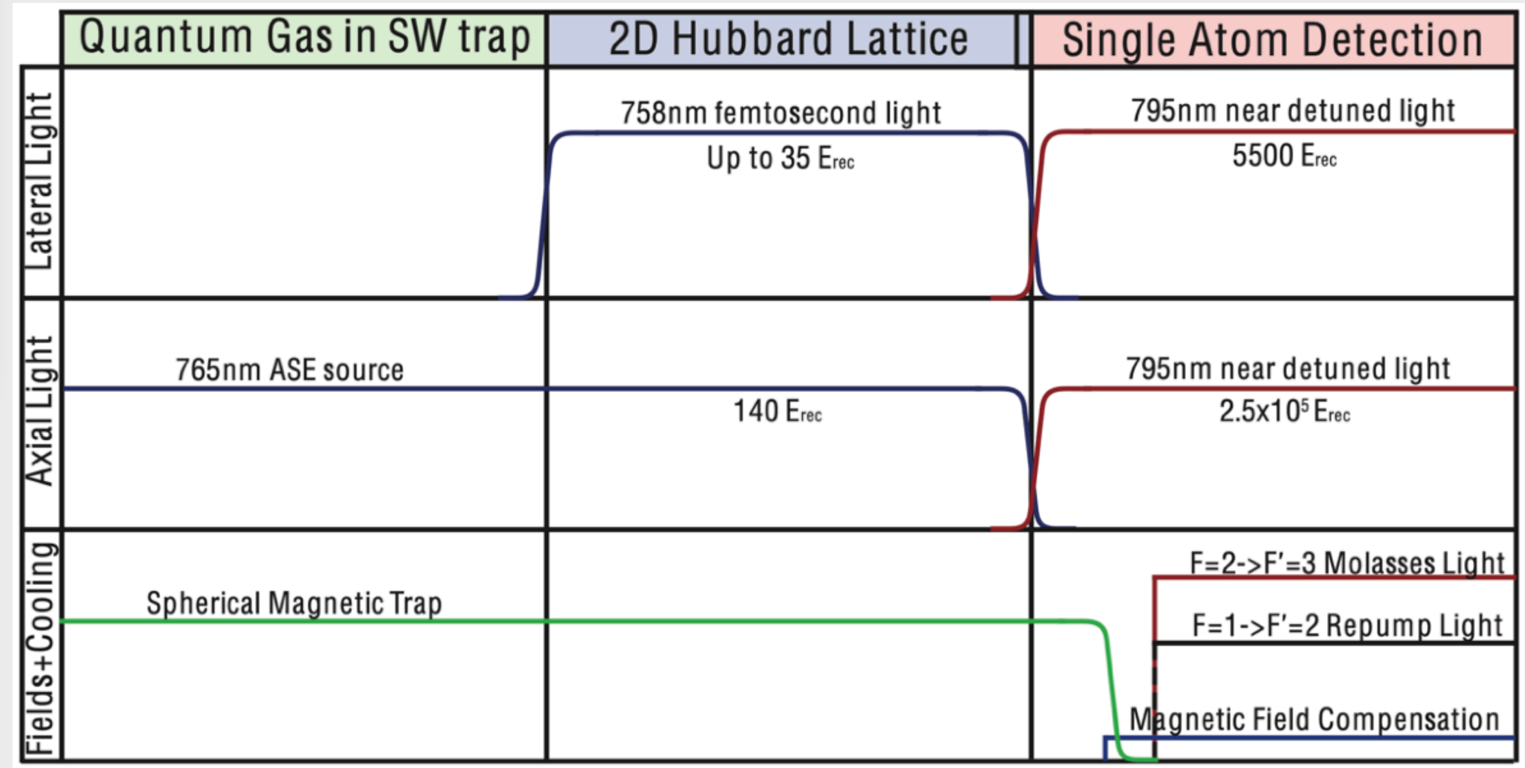
Pinning lattice
1 s

necessitates laser cooling

Quantum gas microscopes

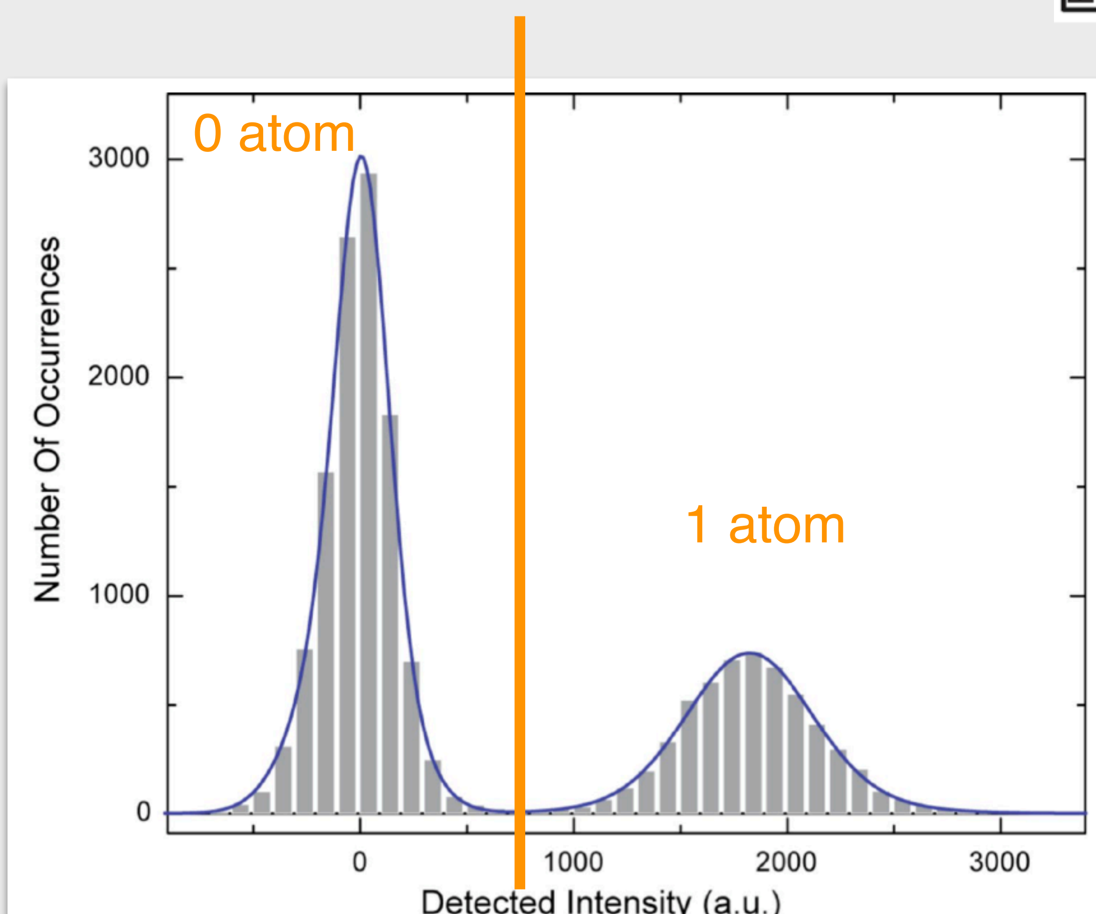


Gillen PhD thesis (Greiner's group 2009)



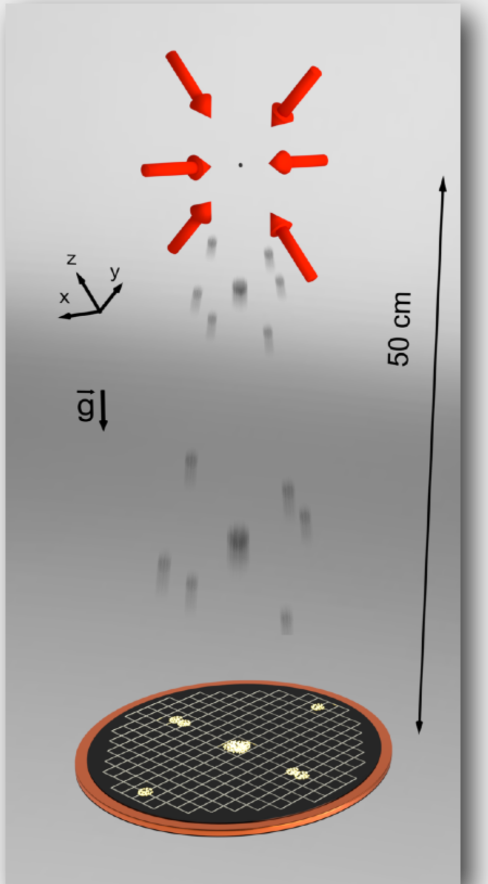
Physics lattice
10-100 ms

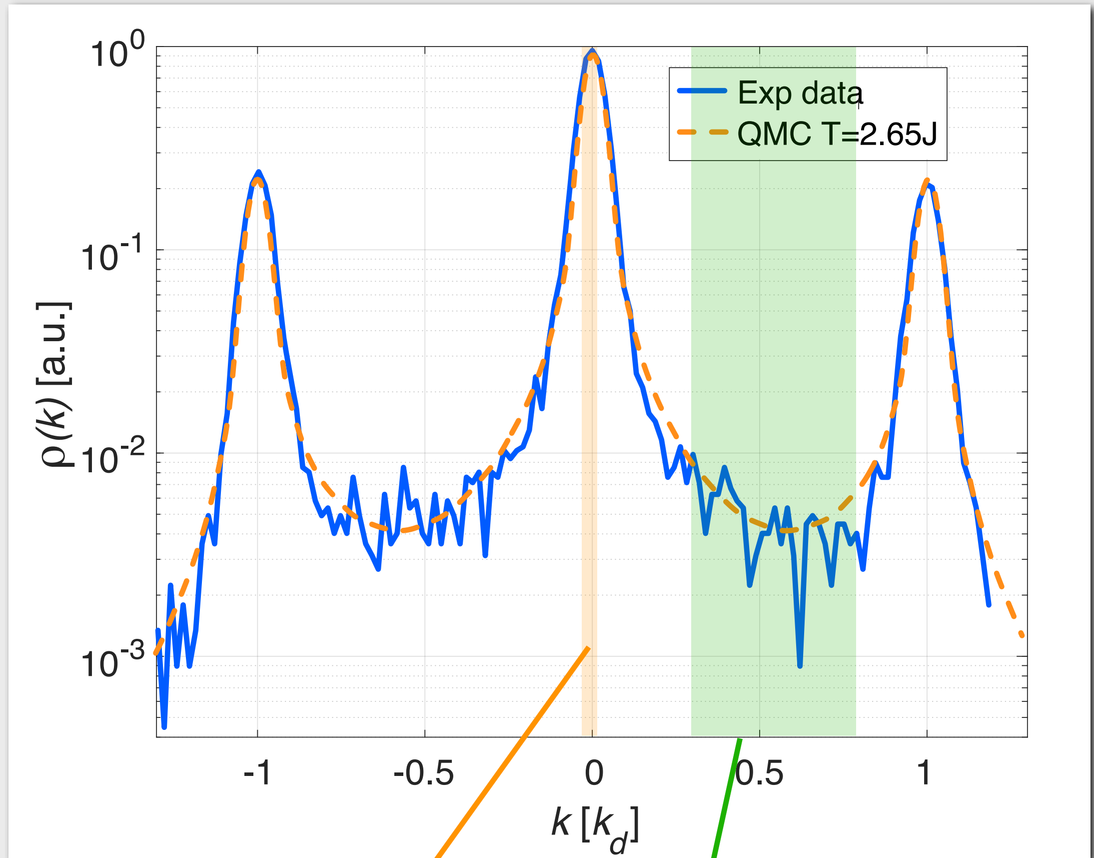
Pinning lattice
1 s

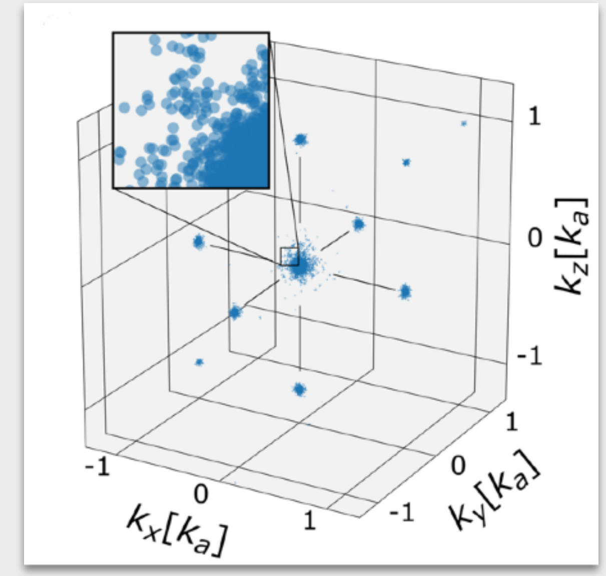


no more than one atom/site due to **light-assisted collisions** in the pinning lattice

Momentum correlations in lattice BECs





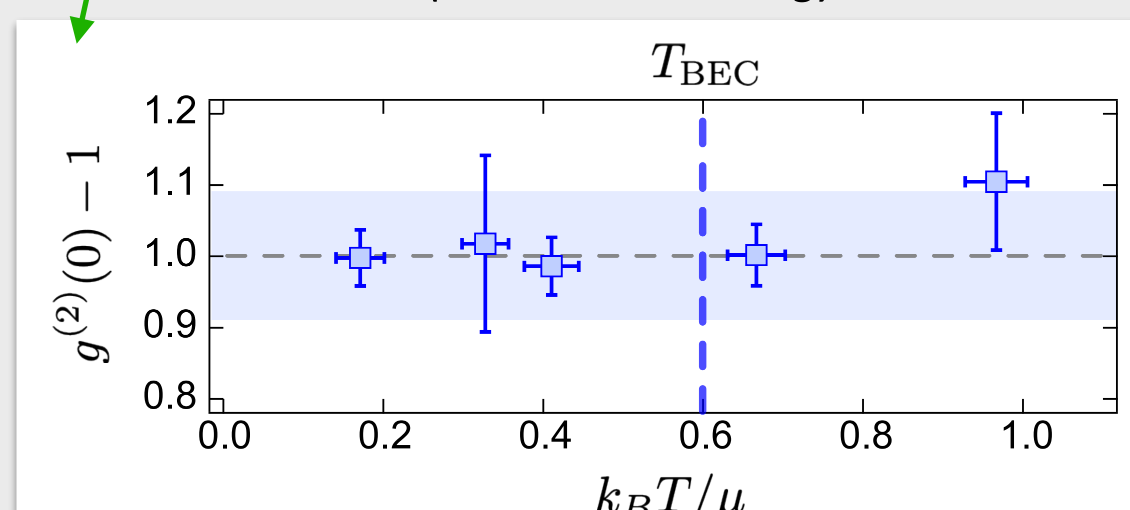


Coherent state: $g_N^{(n)}(0) = 1$

Institut d'Optique - unpublished (2021)

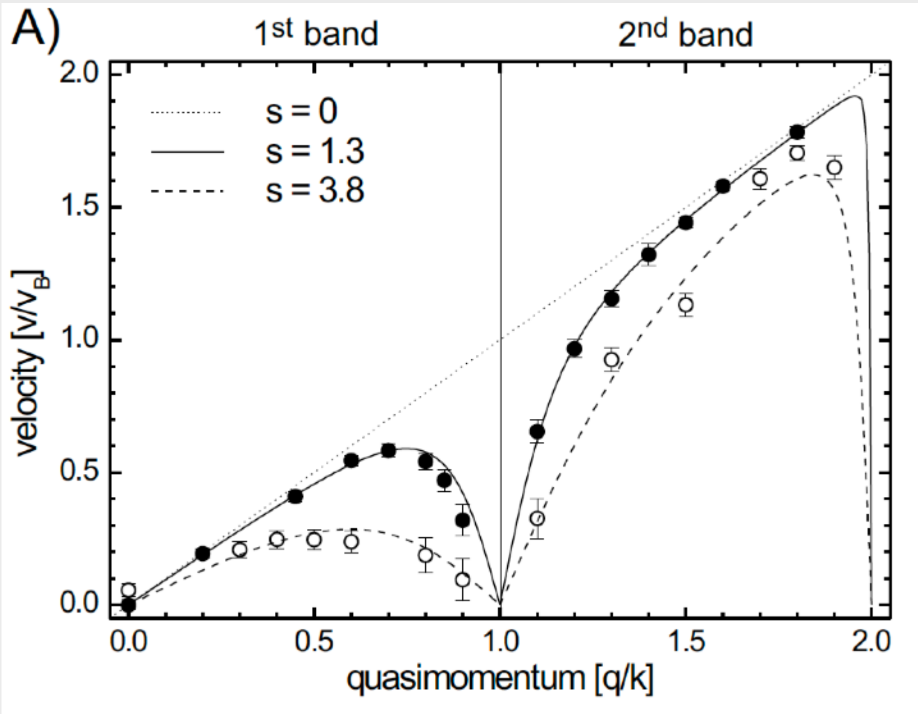
Thermal (chaotic) statistics: $g_N^{(2)}(0) = 2$

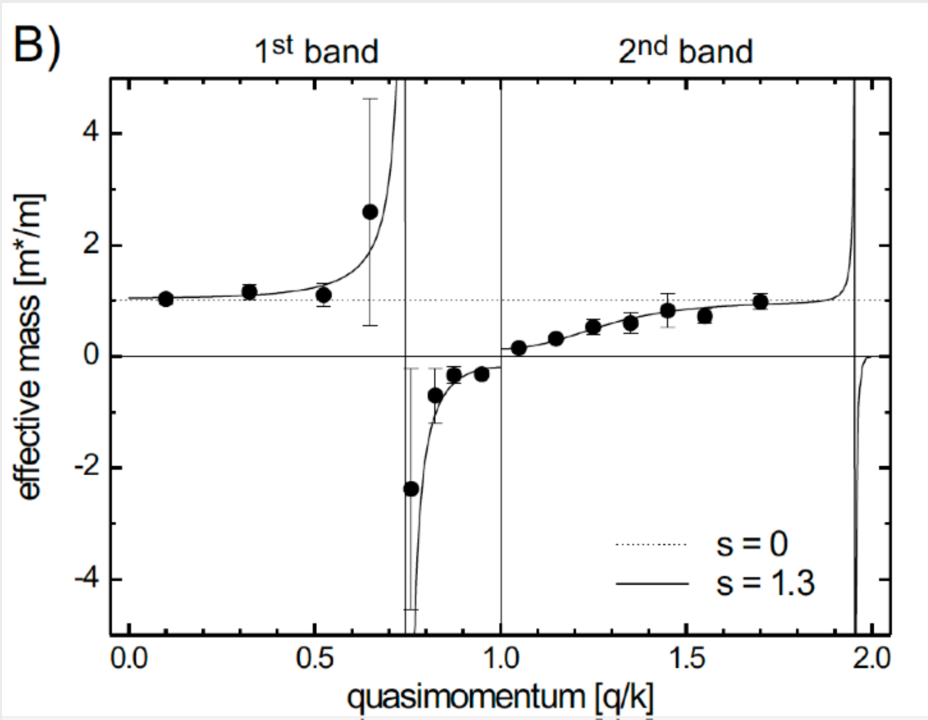
(bosonic bunching)



*Cayla et al. PRL **125**, 165301 (2020)*

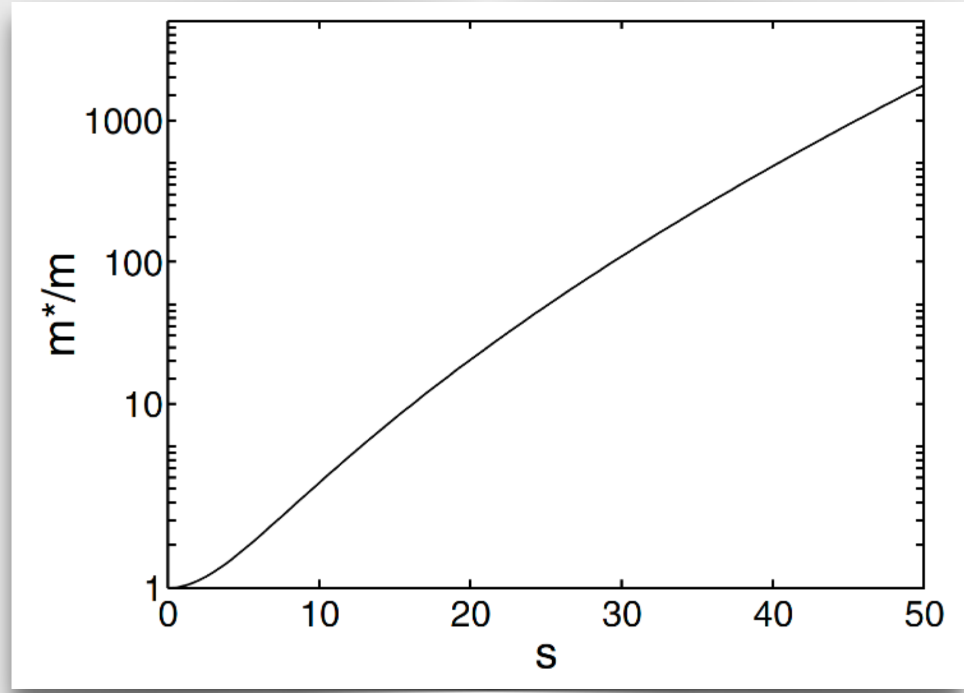
BEC in a 1D lattice





*Fallani et al. PRL **91**, 240405 (2003)*

Effective mass at the center of the Brillouin zone



*Kramer et al. PRL **88**, 180404 (2002)*

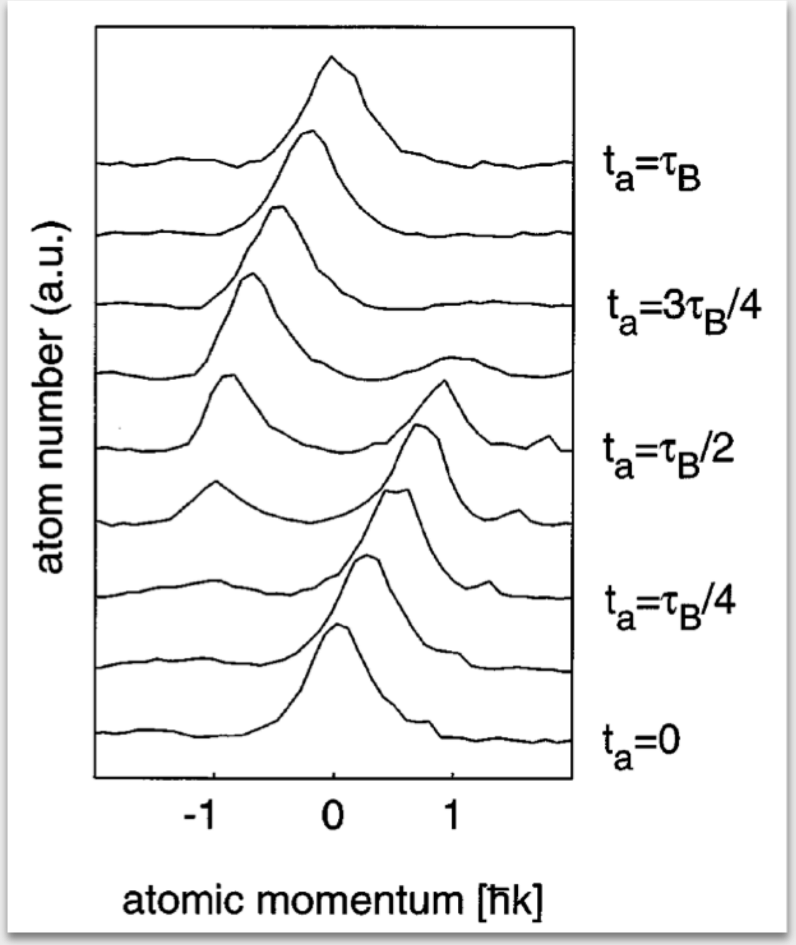
Bloch oscillations

PHYSICAL REVIEW B VOLUME 46, NUMBER 11 15 SEPTEMBER 1992-I

Optical investigation of Bloch oscillations in a semiconductor superlattice

J. Feldmann,* K. Leo,† J. Shah, D. A. B. Miller, and J. E. Cunningham
AT&T Bell Laboratories, Holmdel, New Jersey 07733

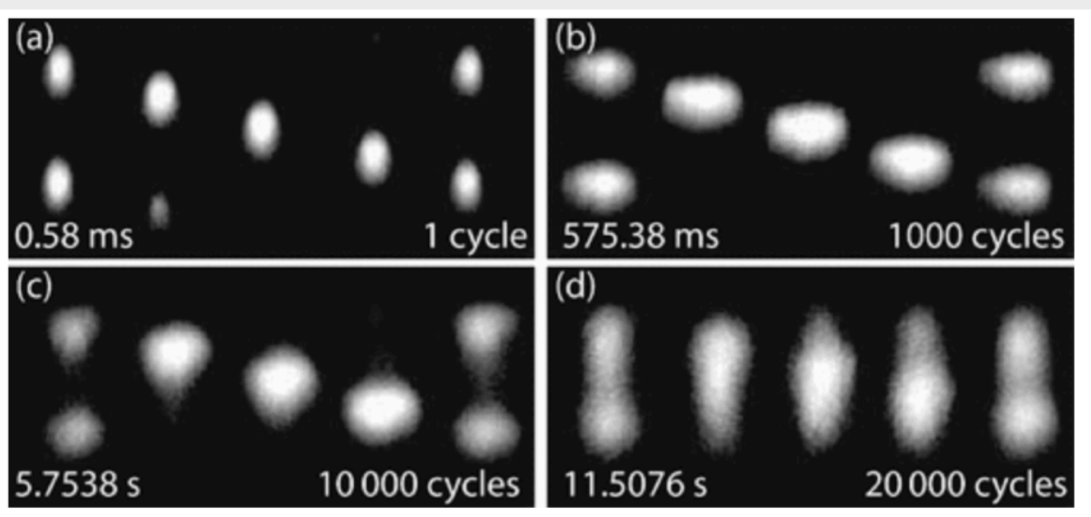
T. Meier, G. von Plessen, A. Schulze, P. Thomas, and S. Schmitt-Rink
Department of Physics and Materials Sciences Center, Philipps-University, W-3550 Marburg, Germany
(Received 27 April 1992)



*Dahan et al. PRL **76**, 4508 (1996)*

Control of Interaction-Induced Dephasing of Bloch Oscillations

M. Gustavsson, E. Haller, M. J. Mark, J. G. Danzl, G. Rojas-Kopeinig, and H.-C. Nägerl
Phys. Rev. Lett. **100**, 080404 – Published 28 February 2008



Precise measurement of h / m_{Rb} using Bloch oscillations in a vertical optical lattice: Determination of the fine-structure constant

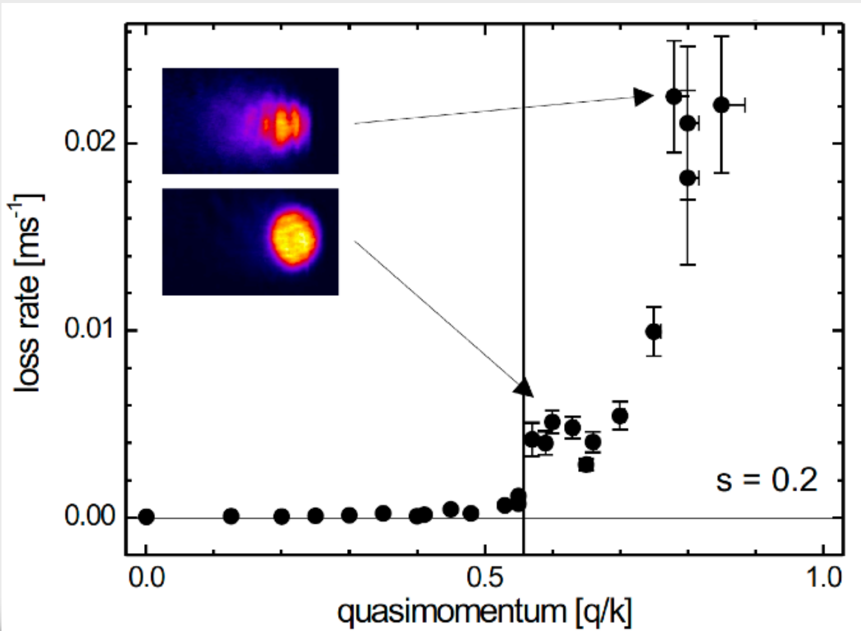
Pierre Cladé, Estefania de Mirandes, Malo Cadoret, Saïda Guellati-Khélifa, Catherine Schwob, François Nez, Lucile Julien, and François Biraben
Phys. Rev. A **74**, 052109 – Published 21 November 2006

Precision Measurement of Gravity with Cold Atoms in an Optical Lattice and Comparison with a Classical Gravimeter

N. Poli, F.-Y. Wang, M. G. Tarallo, A. Alberti, M. Prevedelli, and G. M. Tino
Phys. Rev. Lett. **106**, 038501 – Published 18 January 2011

Physics See Synopsis: Less wiggle room for the gravitational constant

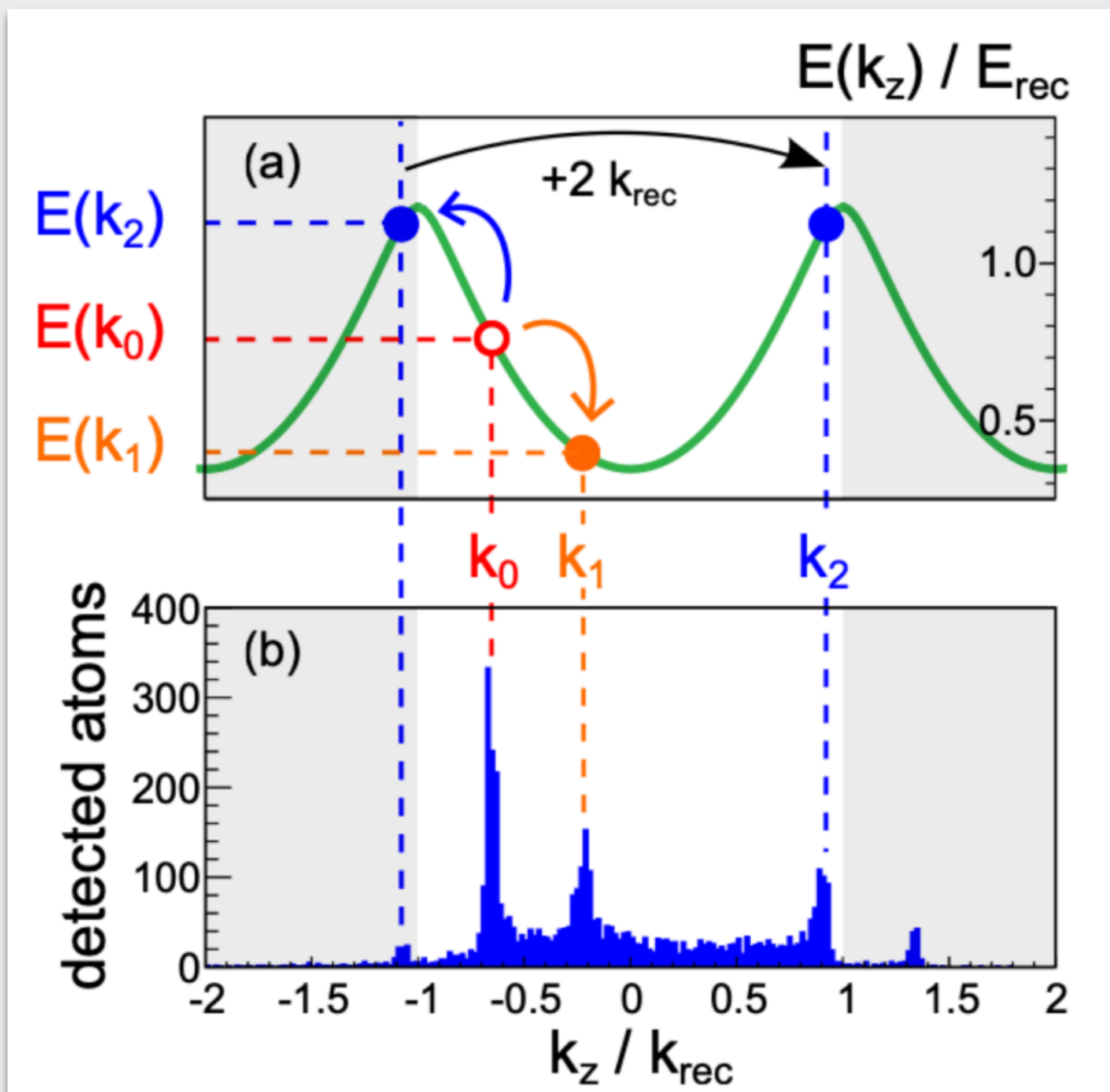
Dynamical instabilities in a 1D lattice



Observation of Dynamical Instability for a Bose-Einstein Condensate in a Moving 1D Optical Lattice

L. Fallani, L. De Sarlo, J. E. Lye, M. Modugno, R. Saers, C. Fort, and M. Inguscio

Phys. Rev. Lett. **93**, 140406 – Published 29 September 2004



Tunable source of correlated atom beams

M. Bonneau, J. Ruaudel, R. Lopes, J.-C. Jaskula, A. Aspect, D. Boiron, and C. I. Westbrook

Phys. Rev. A **87**, 061603(R) – Published 17 June 2013