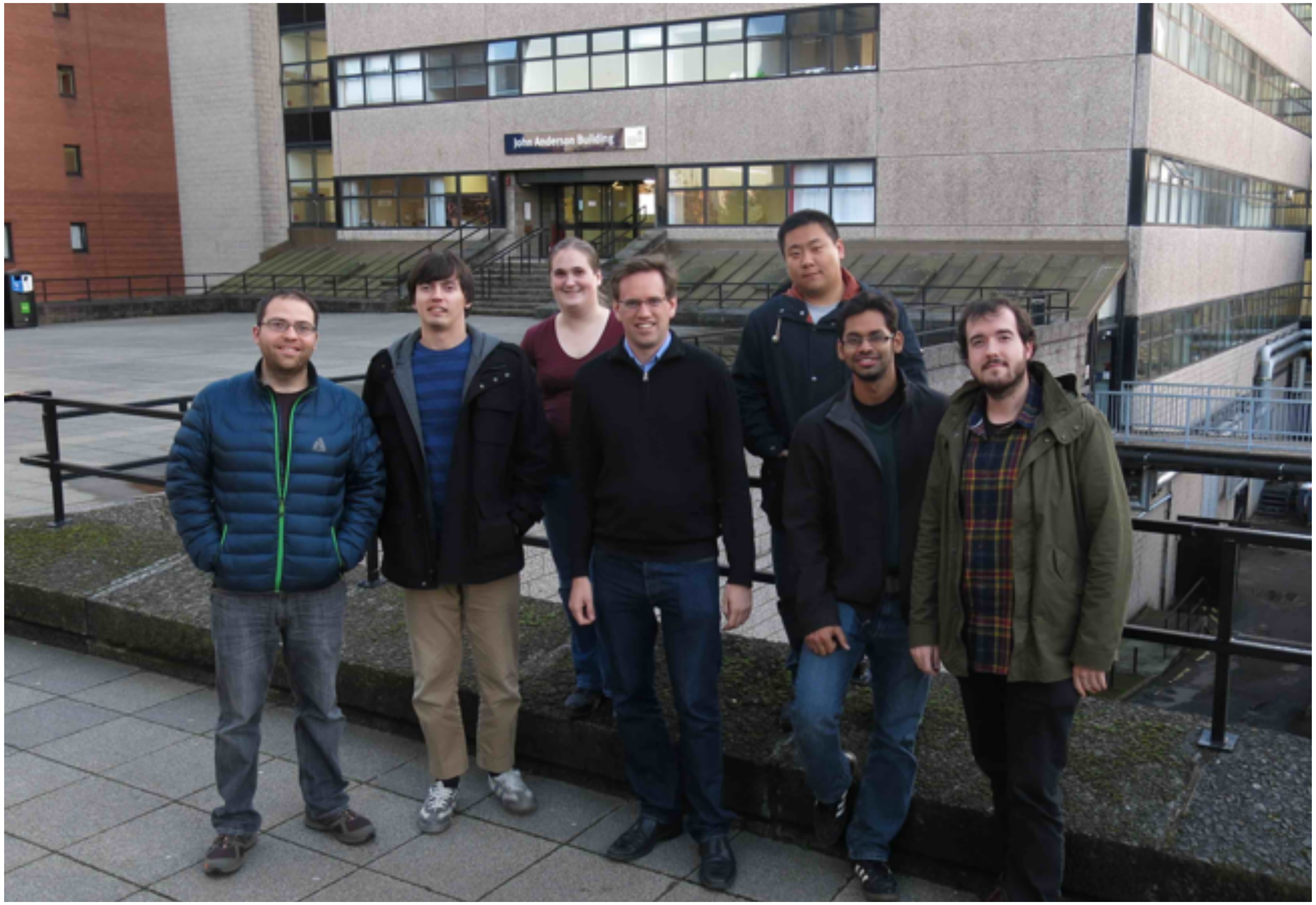
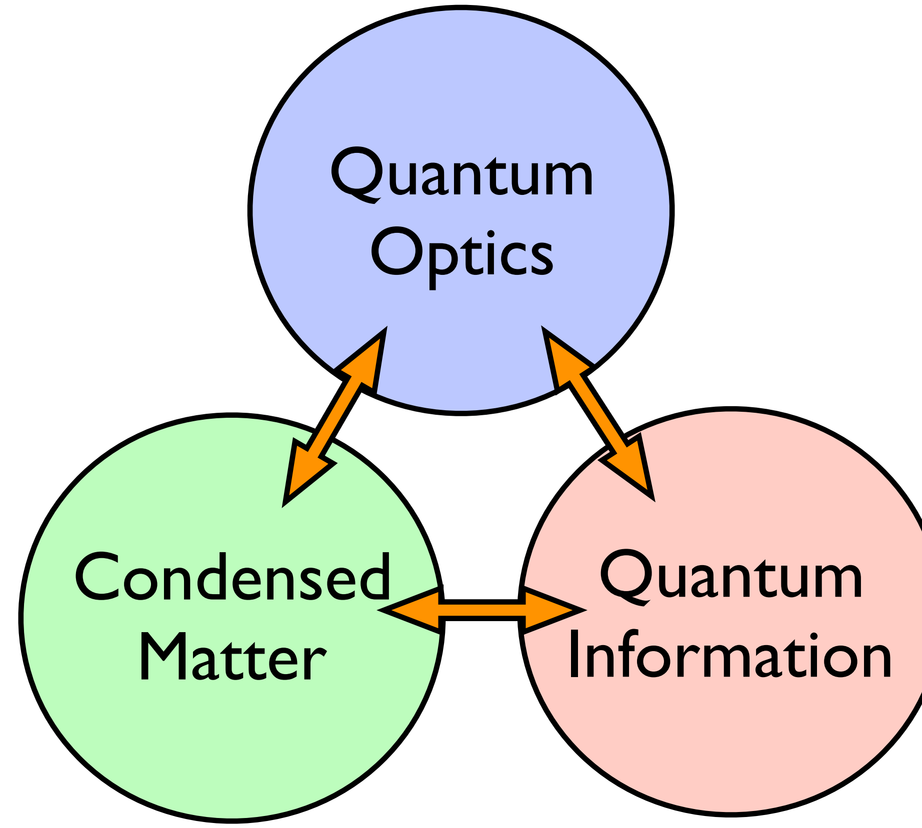
Microscopic control of quantum gases and quantum simulation

Andrew Daley

Department of Physics and SUPA
University of Strathclyde





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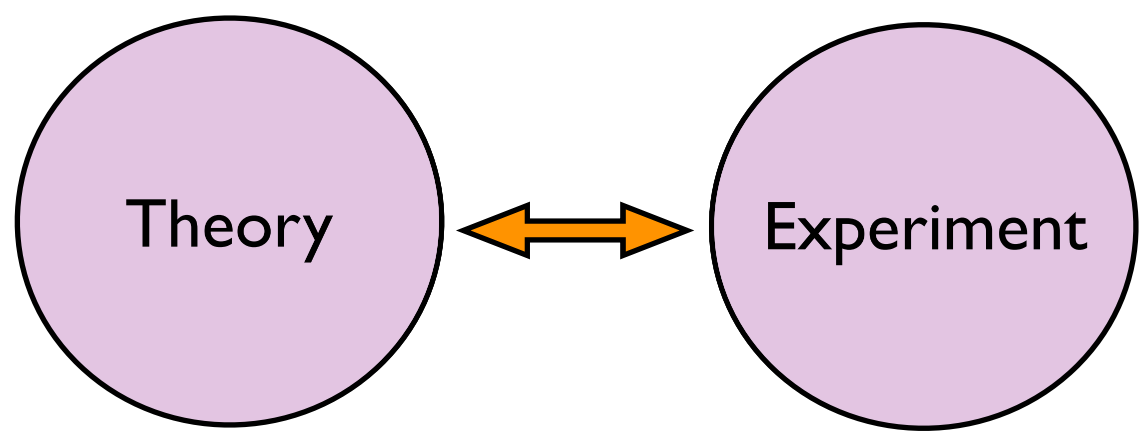
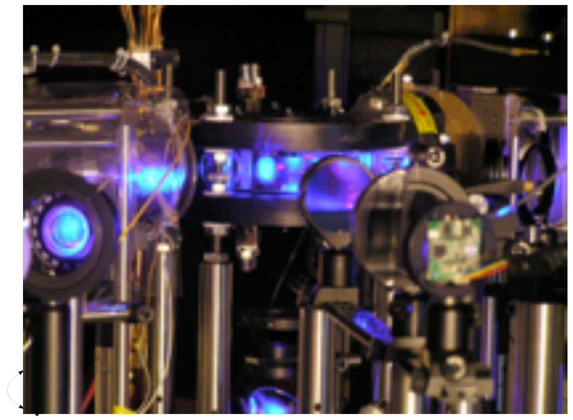
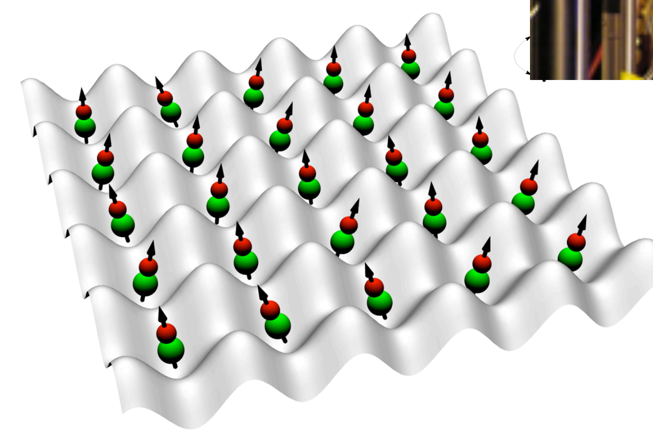


Outline

Overview of Quantum Simulation

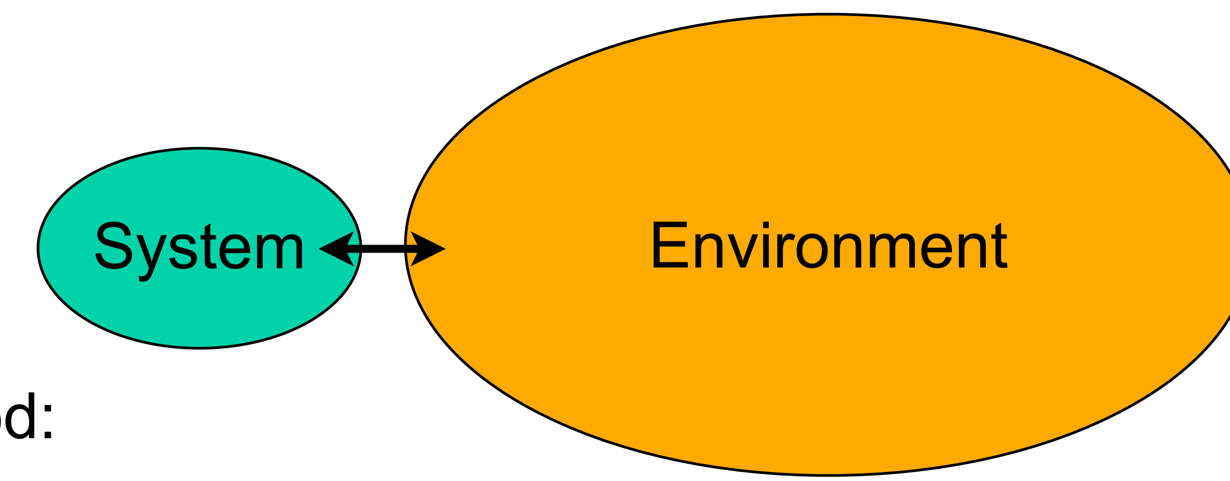
- Analogue and digital quantum simulators
- Microscopic description of cold atomic gases
- Example: The Bose-Hubbard Model
- Recent developments and extensions
- Perspectives





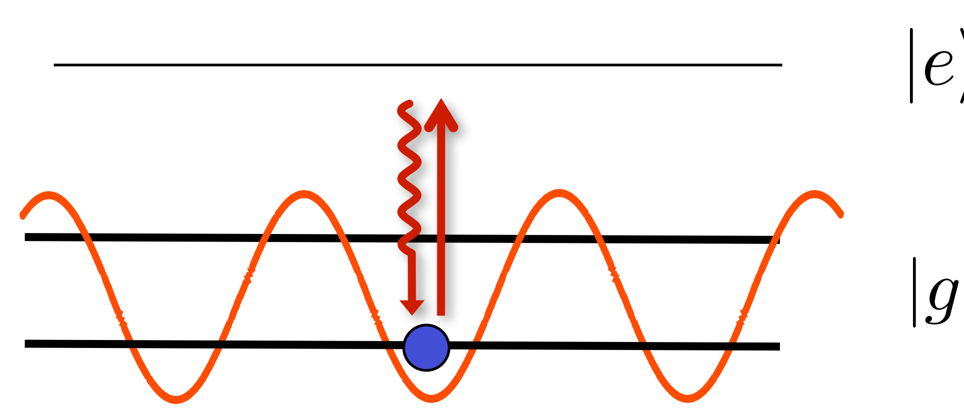
Microscopic Details for optical lattices

- Microscopic treatment of interactions
- Band structure and the Bose-Hubbard model



Open many-body quantum systems

- Also decoherence is microscopically understood:
  Heating in optical lattices
- Decoherence can be your friend:
  Losses are good!
  Dark state cooling and state preparation



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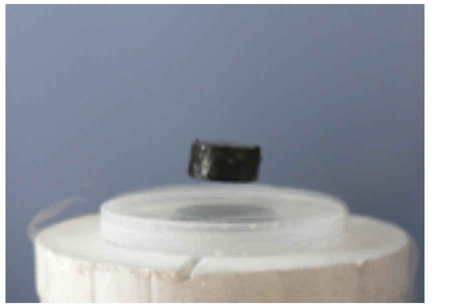
Analogue and Digital Quantum Simulators

“...it is difficult to simulate quantum mechanics on a classical computer”

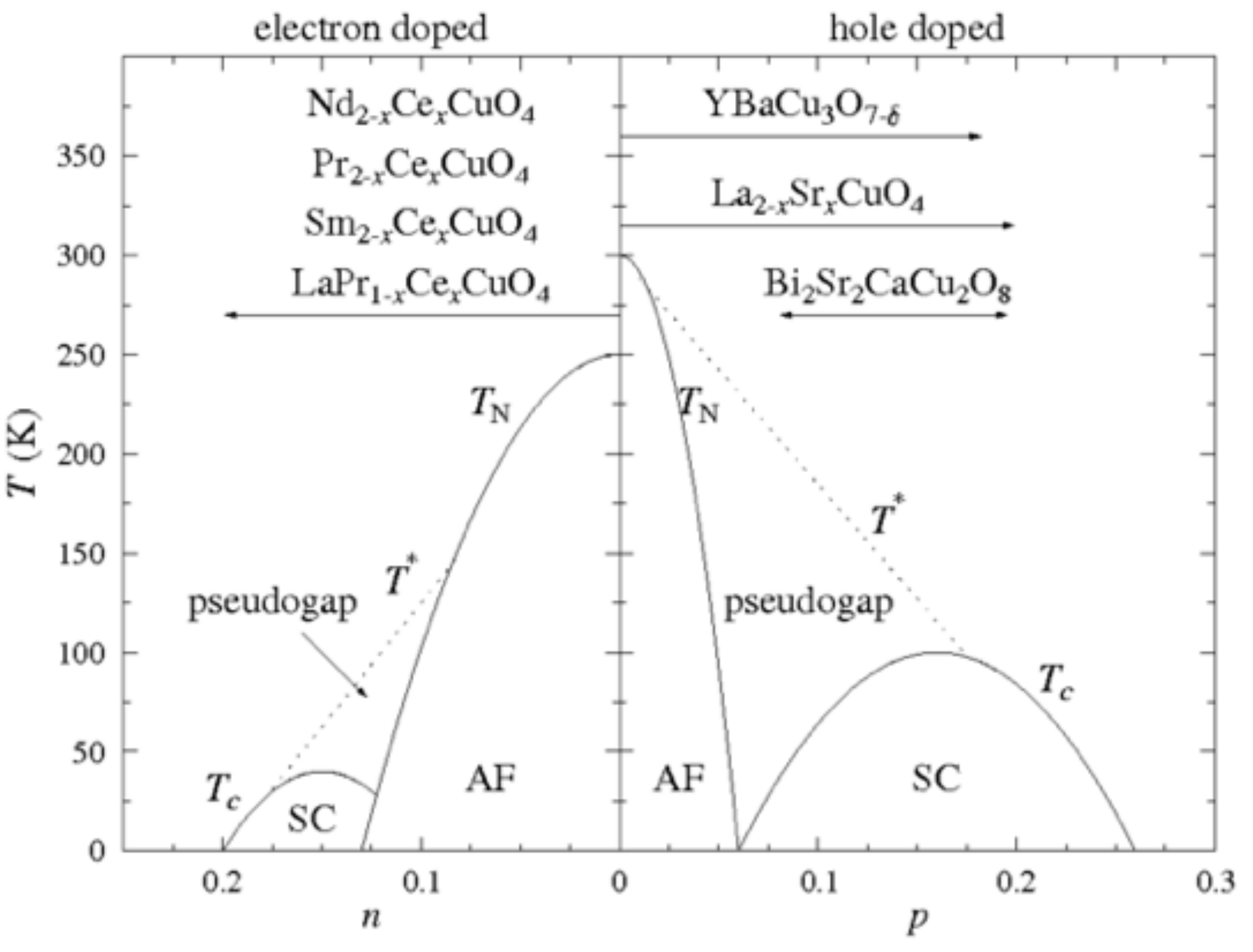
R. Feynman, 1986

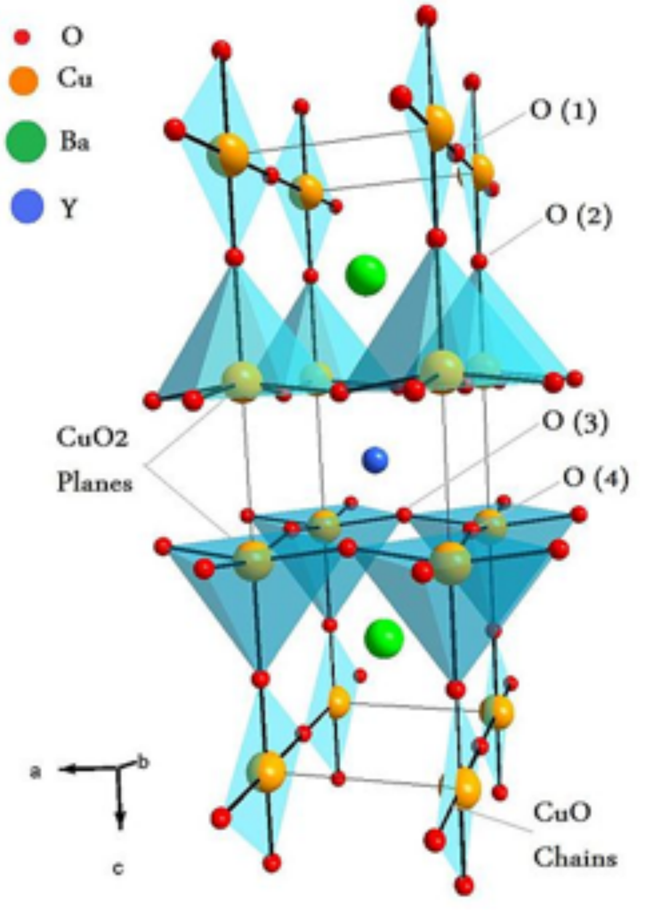
“Nature isn't classical, and if you want to make a simulation of Nature, you'd better make it quantum mechanical, and by golly it's a wonderful problem, because it doesn't look so easy.”

Example problem - Understand high-Tc superconductivity



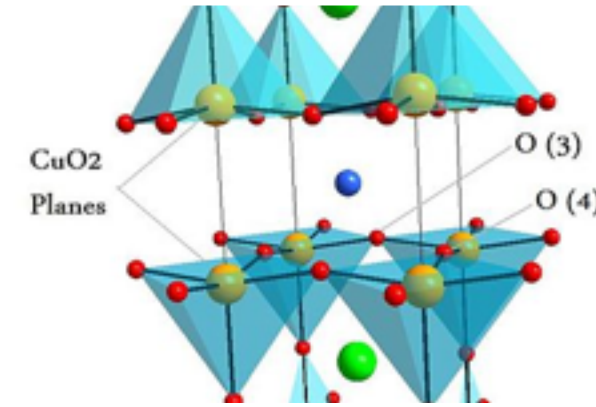
Simple model for high Tc superconductivity of cuprates?



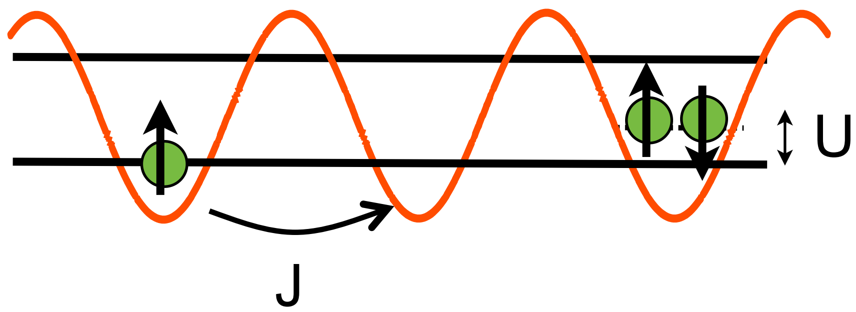


- Discovered 1986 (Georg Bednorz and K. Alex Müller, Nobel Prize 1987)
- Mechanism still not well understood

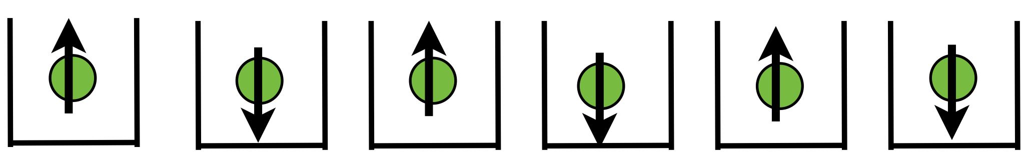
Example problem - Fermi Hubbard model



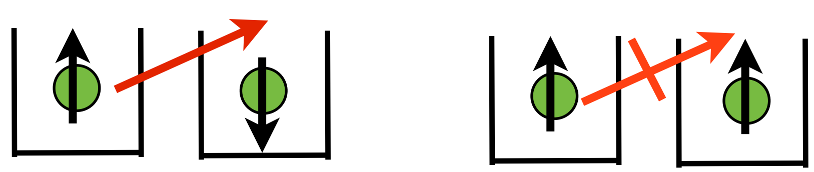
Simple model for high Tc superconductivity of cuprates?

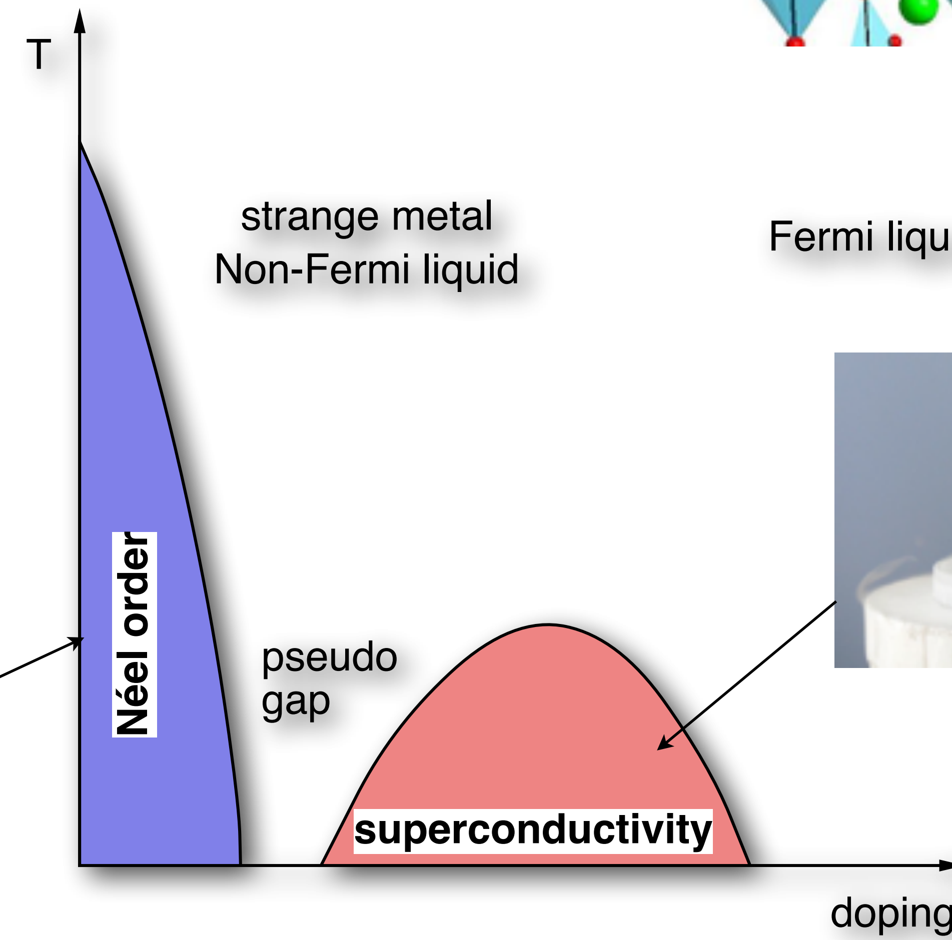


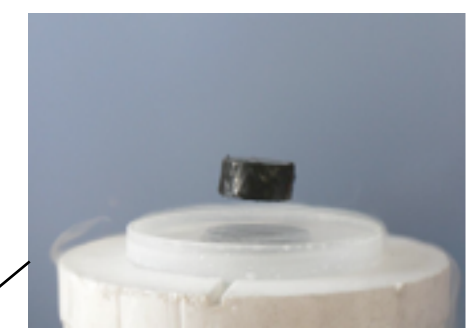
$$H = -J \sum_{\langle i,j \rangle,\sigma} c^\dagger_{i,\sigma} c_{j,\sigma} + U \sum_i c^\dagger_{i,\uparrow} c^\dagger_{i,\downarrow} c_{i,\downarrow} c_{i,\uparrow}$$



$\sim -\frac{J^2}{U}$





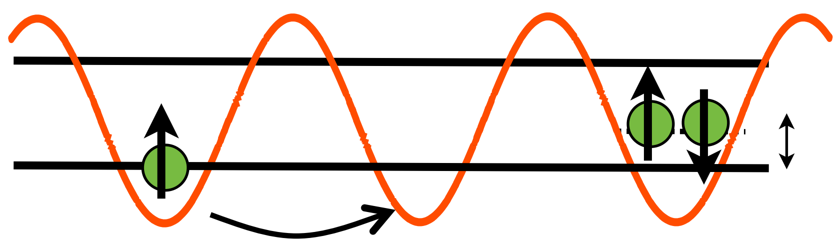


Deceptively simple

- Intractable to analytical methods (away from half-filling)
- Numerical methods fail: Exponentially large Hilbert space
  Fermions - no known Monte-Carlo methods

Why are quantum systems hard to simulate (classically) in general?

- Because of the exponential growth of the Hilbert space with system size, many-body quantum systems cannot be simulated exactly, e.g., arrange N particles on M sites:



		two species
4,6:	15 states	225 states
7,12:	792 states	627264 states
26,50:	1.2×10^{14} states	1.5×10^{28} states

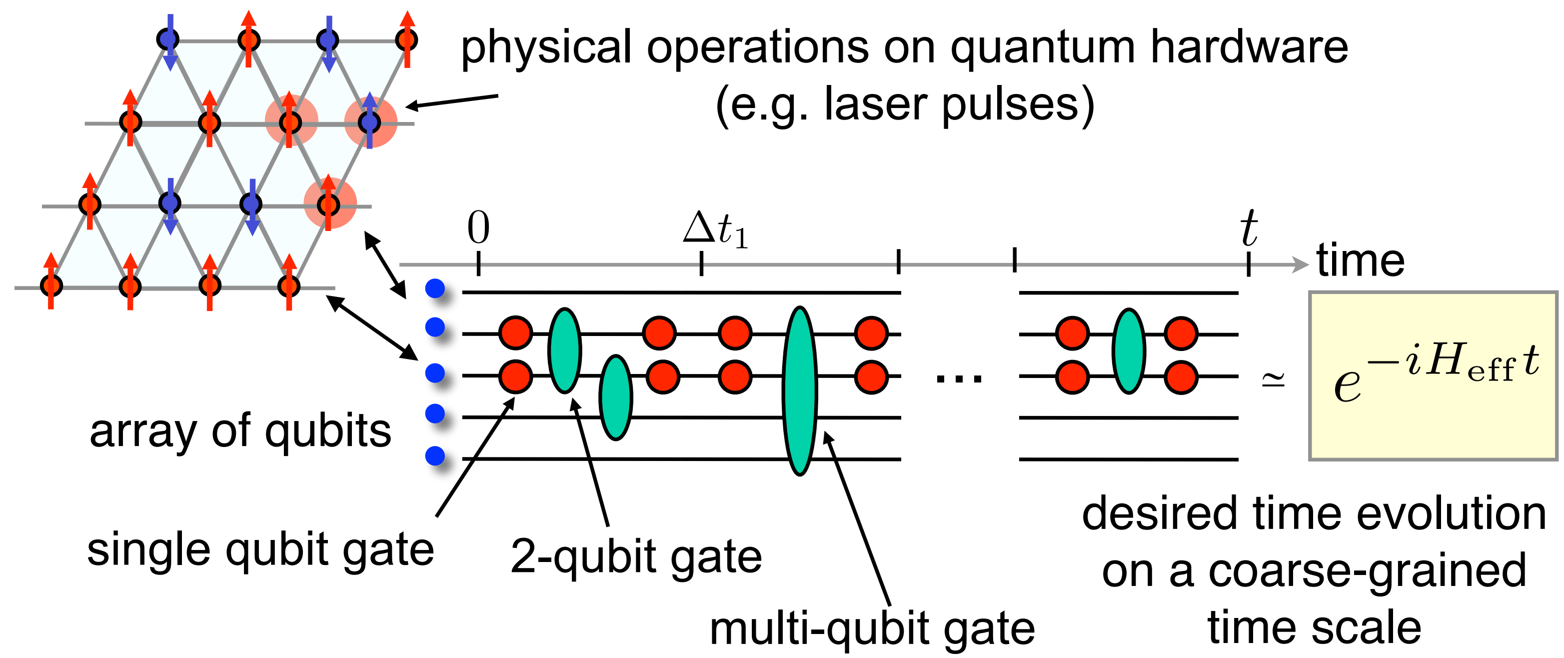
- Specialist tools available for some systems:
  - Density matrix renormalisation group in 1D
  - Unbiased Quantum monte-carlo for Bosons/spins without frustration (sample from path integral)

$$\langle A \rangle = \frac{\sum_l A_l W_l}{\sum_l W_l}$$

for fermions, the weights *W* can be different signs - leading to insurmountable sampling errors for large systems. This is known as the **sign problem**

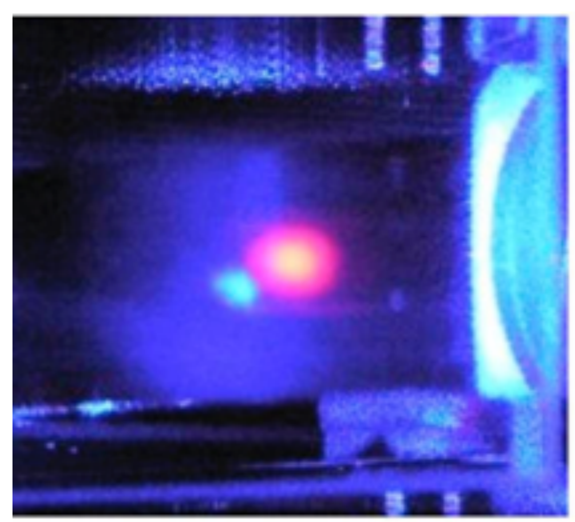
Digital quantum simulation

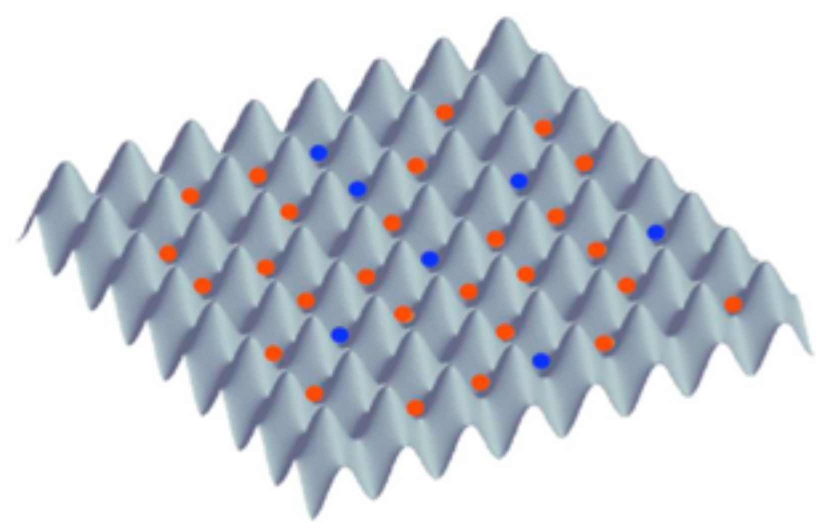
- Use a quantum computer



Analogue quantum simulation (special purpose computing)

- Manipulate a physical system to implement the Hamiltonian





M. Müller, S. Diehl, G. Pupillo, and P. Zoller, *Engineered Open Systems and Quantum Simulations with Atoms and Ions*, Advances In Atomic, Molecular, and Optical Physics 61 (2012), pp. 1–80.

Overview of Quantum Simulation

- Analogue and digital quantum simulators
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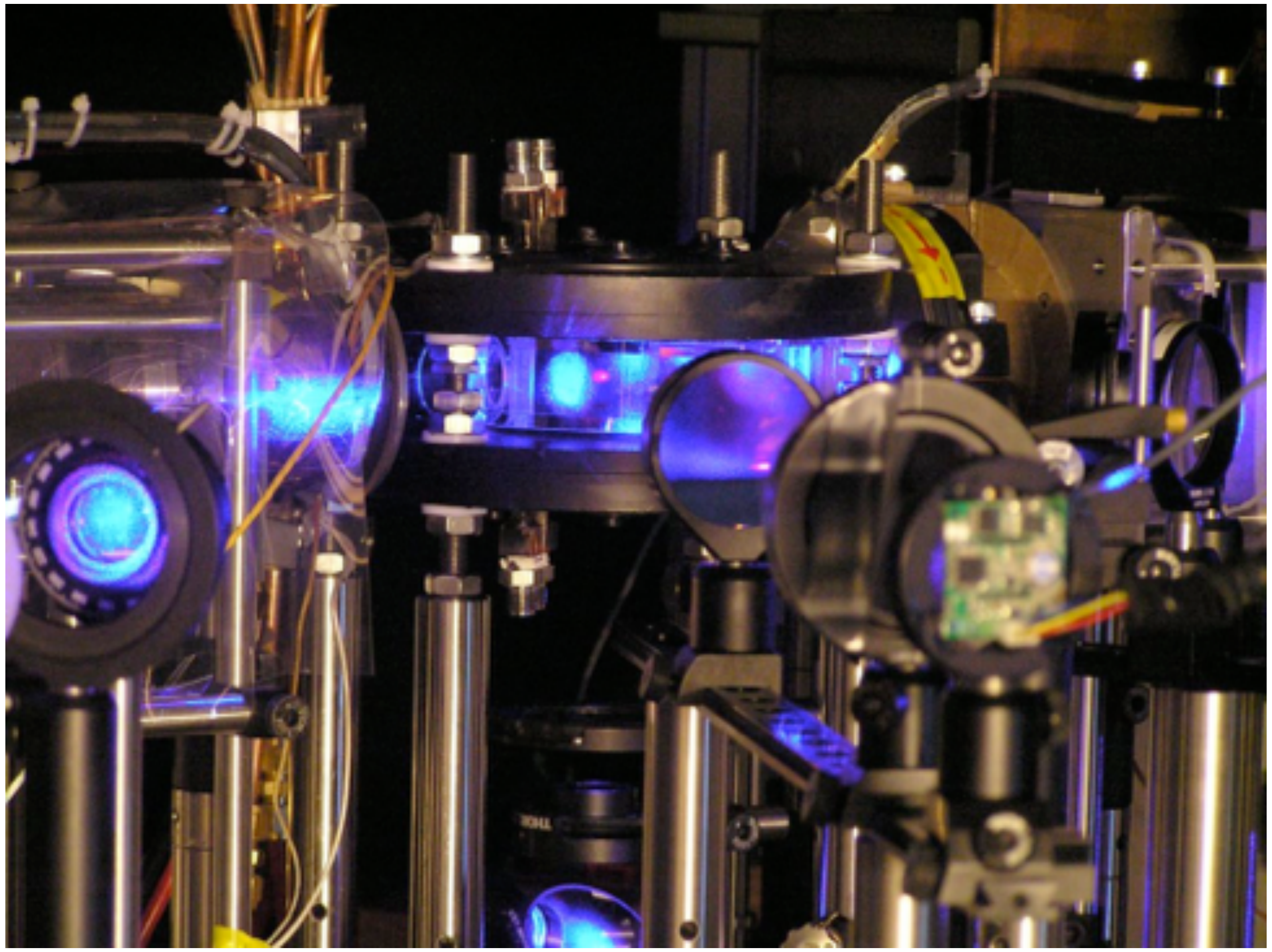
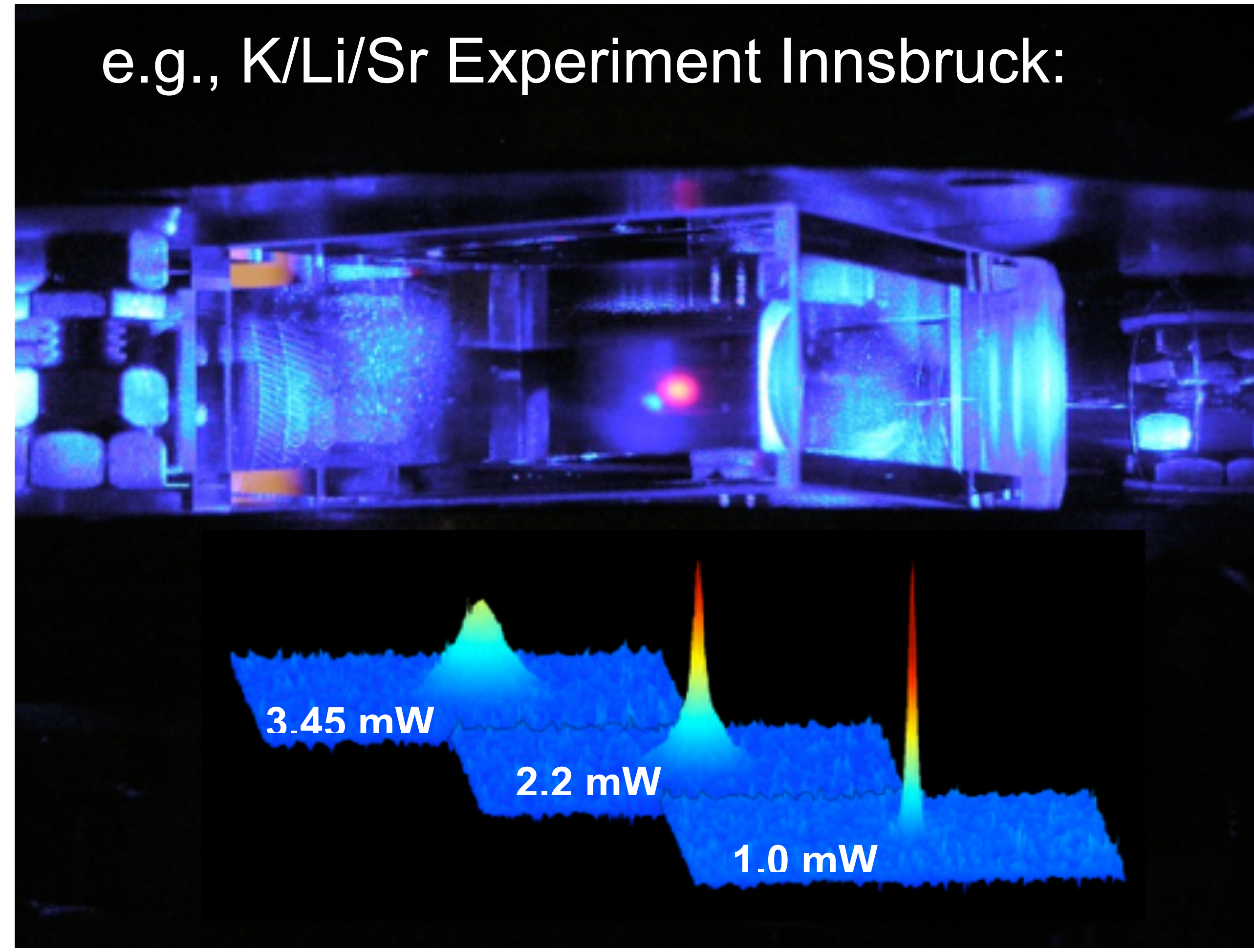
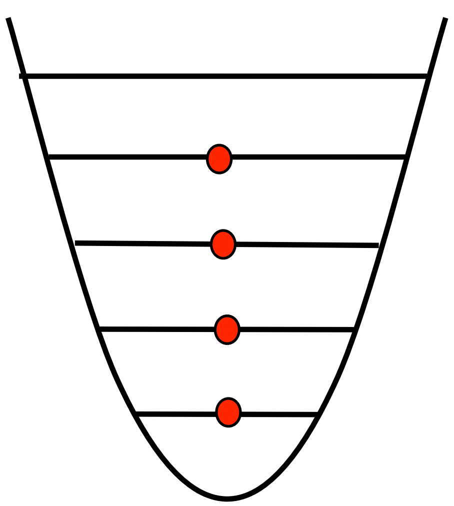
- Example: The Bose-Hubbard Model
- Recent developments and extensions
- Perspectives

Degenerate Bose/Fermi Gases in the laboratory:

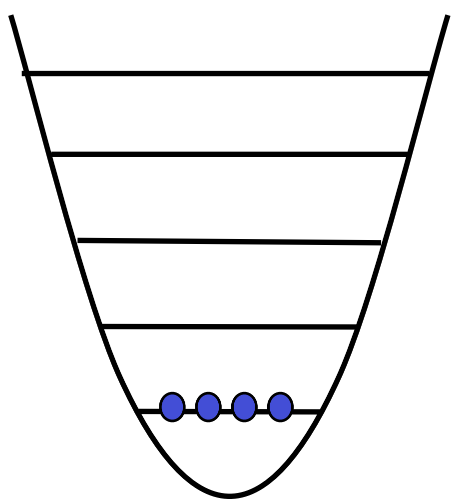




Degenerate Fermi Gas



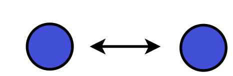
Bose-Einstein Condensate



~100000 atoms

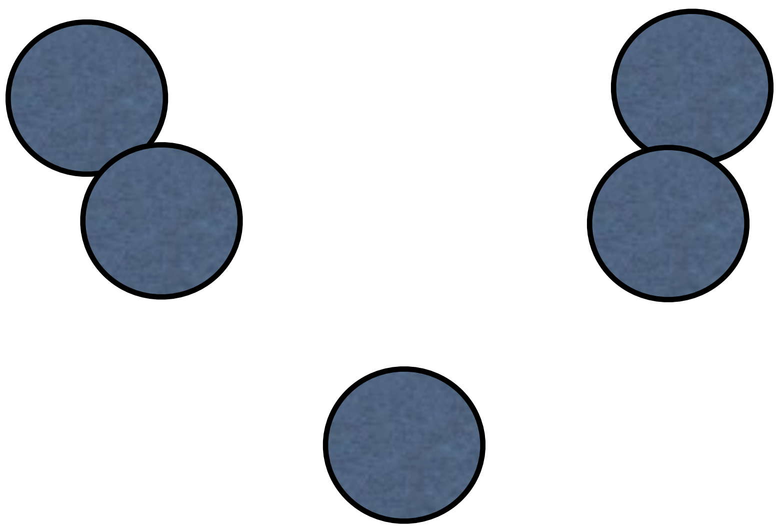
Microscopic control/ understanding

Optical and magnetic traps



2-body interactions
Control via magnetic fields

Microscopic Control: Interactions:

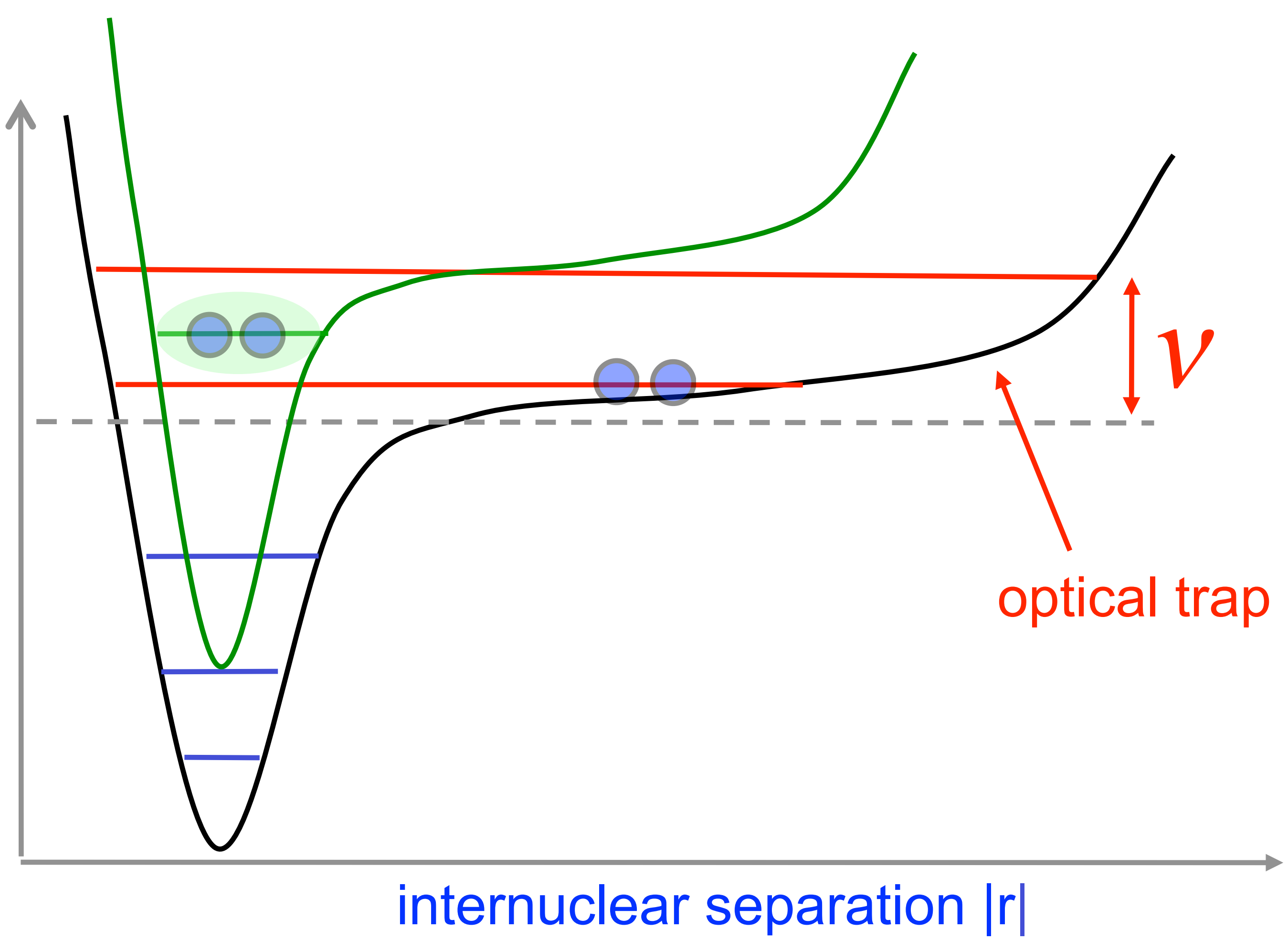


Microscopic understanding of interactions:

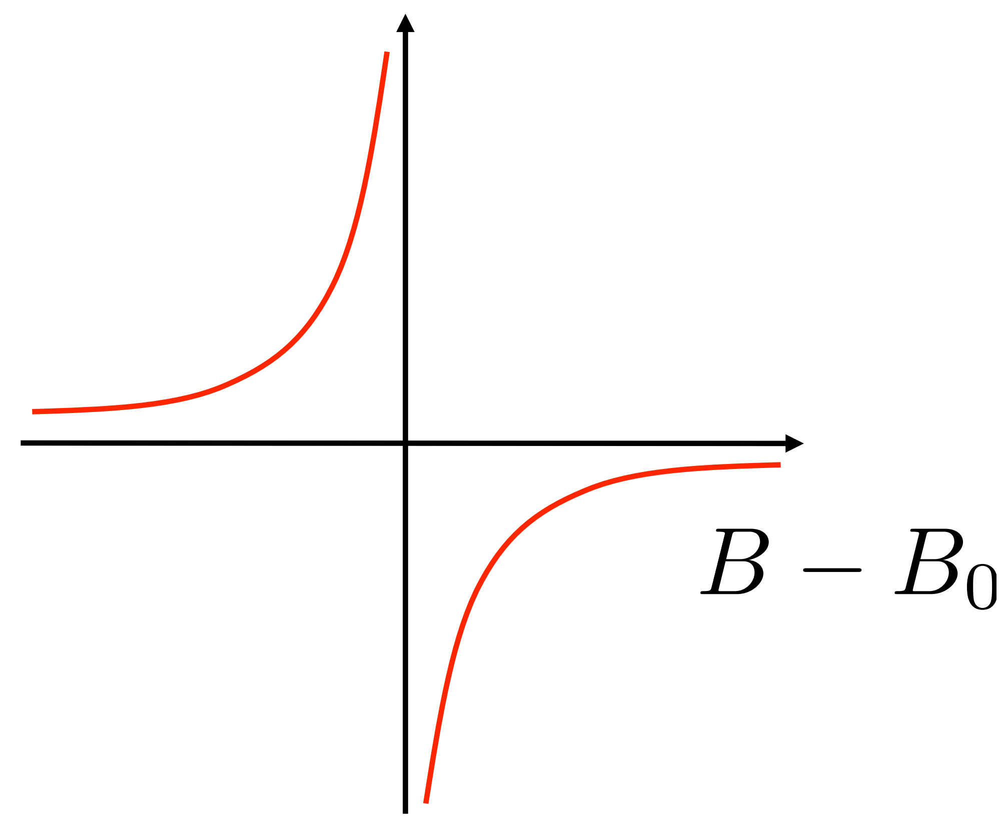
- Dilute gas - three body interactions weak
- Low-energy two-body interactions
- Simple microscopic description

MORE IN TOMORROW'S LECTURE

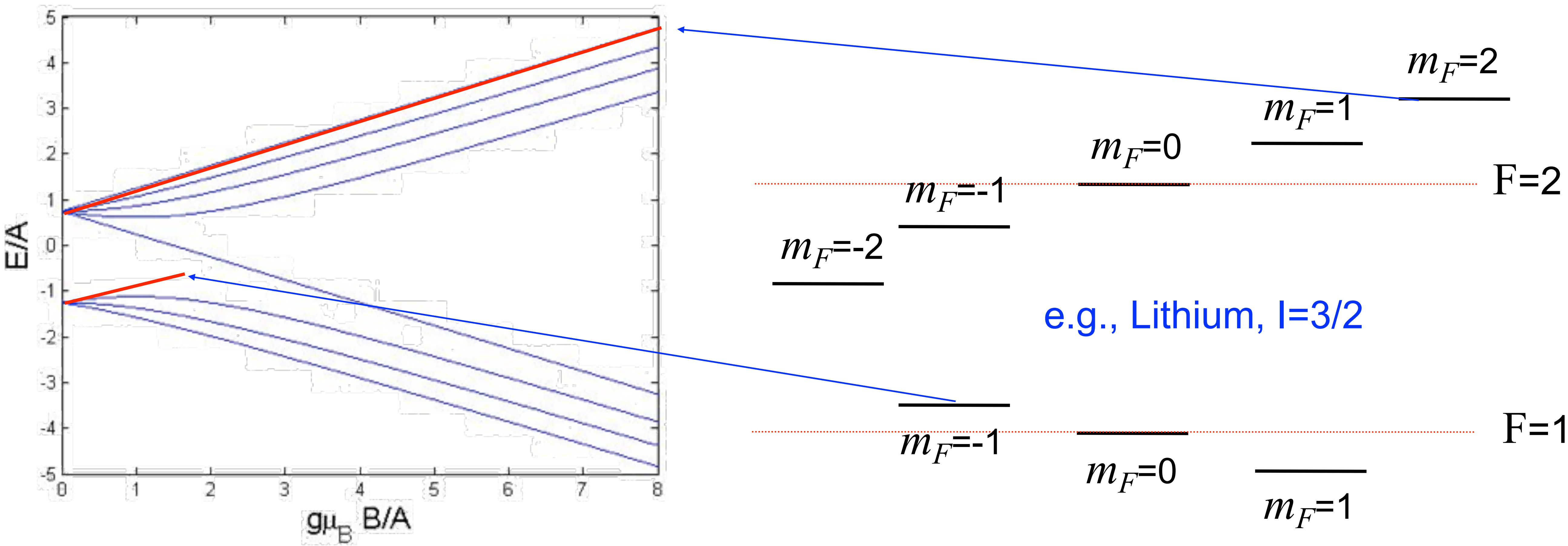
Microscopic Control: Feshbach Resonance



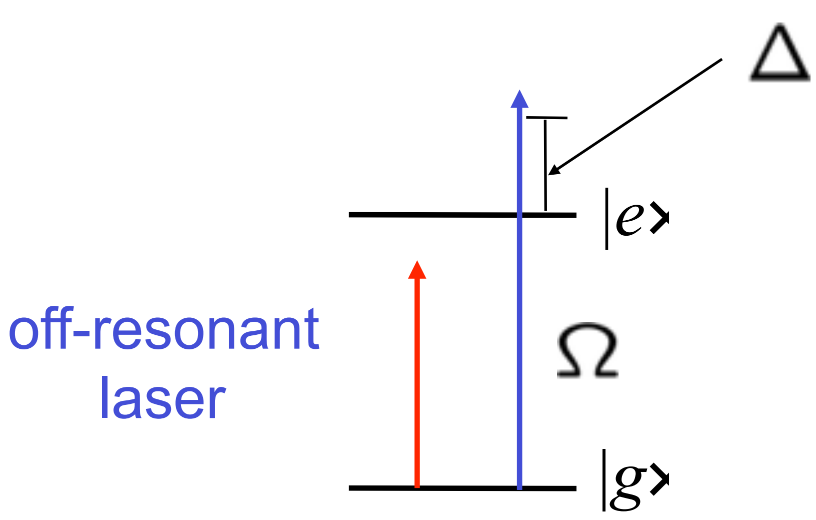
Scattering length
(strength of interactions)



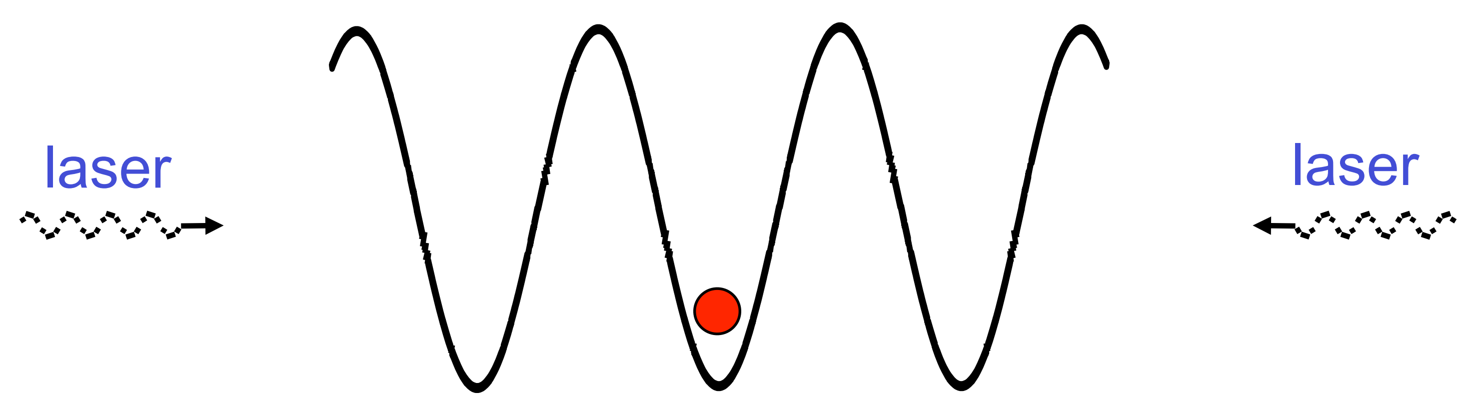
Microscopic Control: Magnetic Traps (Zeeman Shift):



Microscopic Control: Optical Traps (AC-Stark Shift)

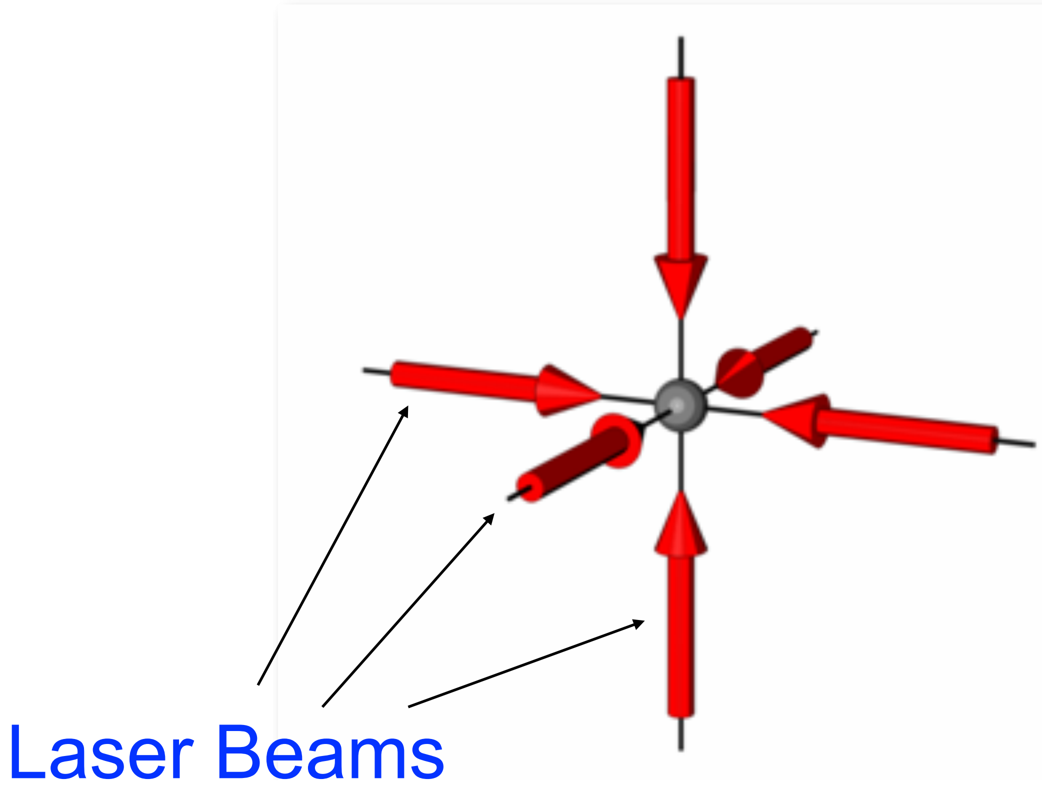


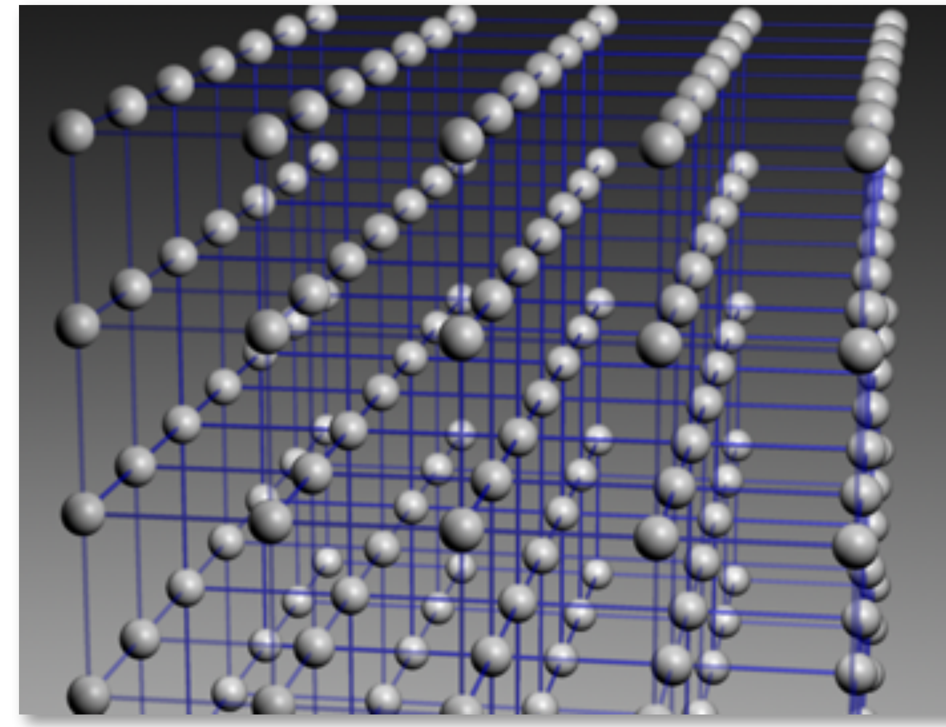
AC Stark shift

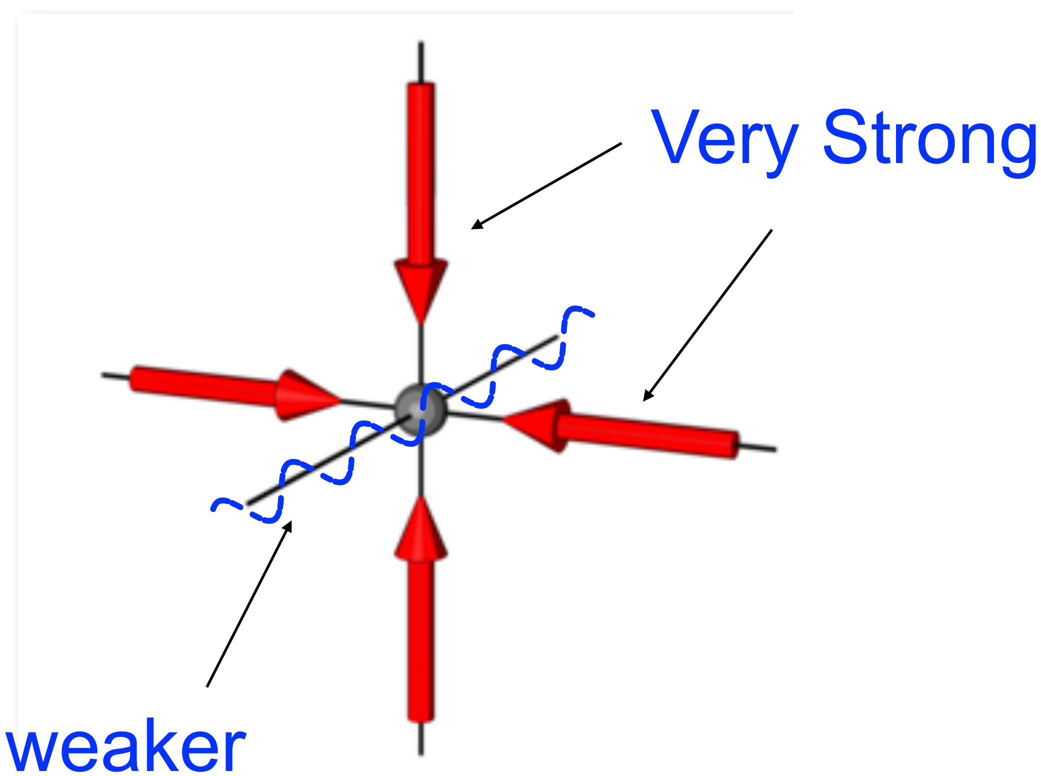


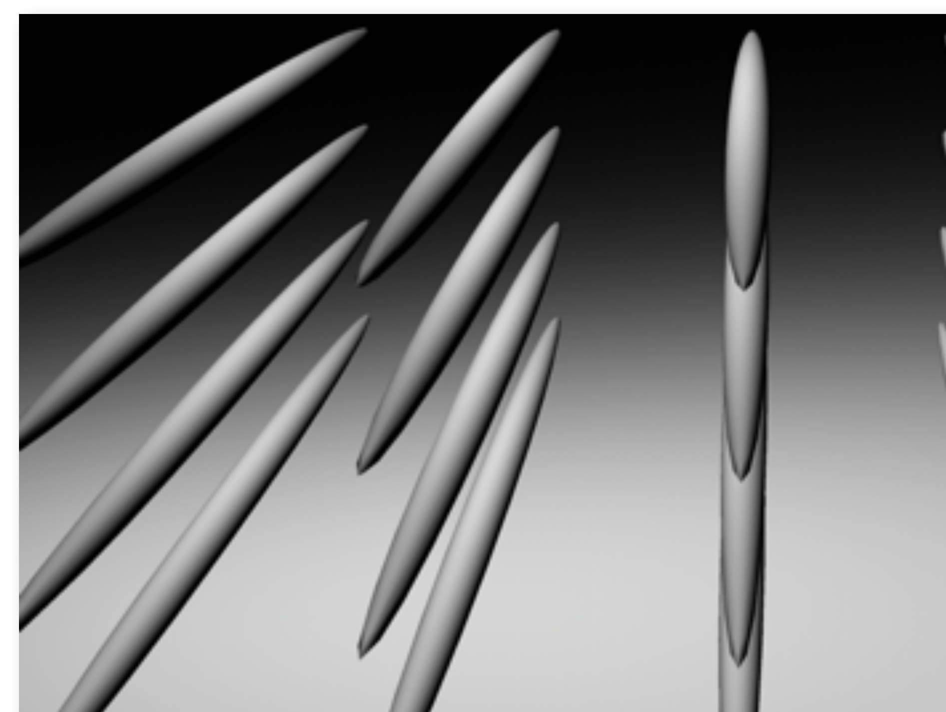
$$V(x) = \alpha(\omega) I = V_0 \sin^2(kx)$$

Optical Lattice Potentials:

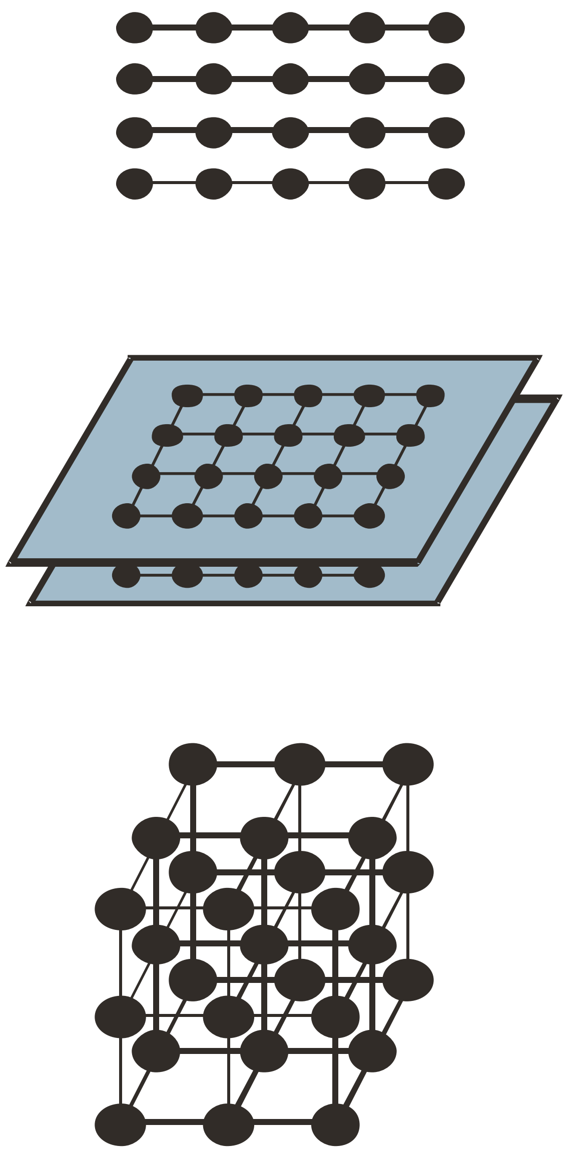




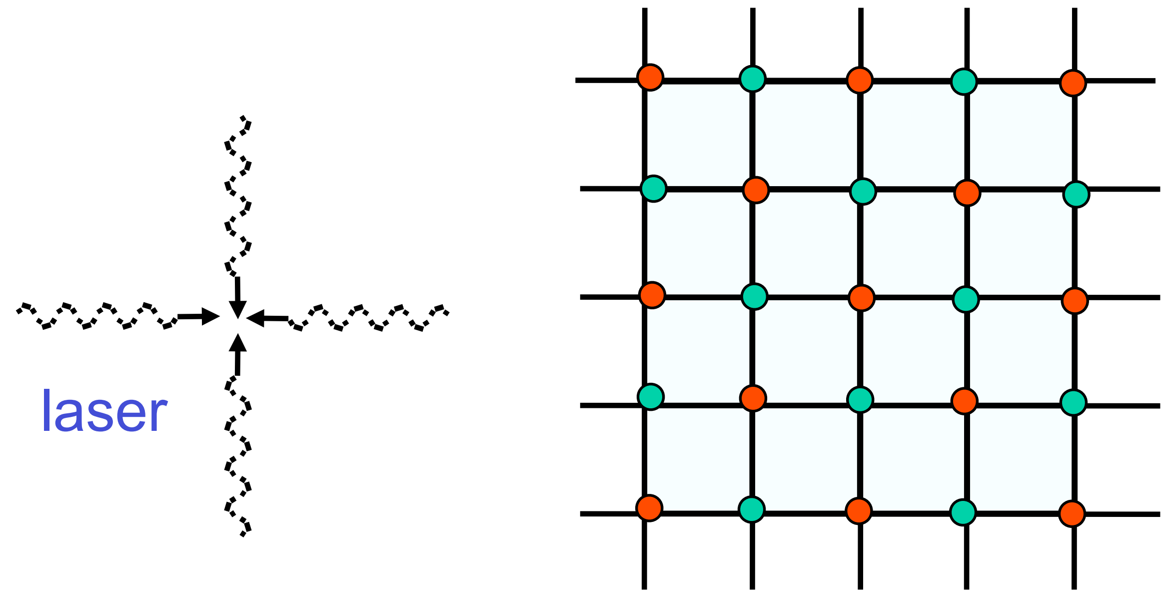




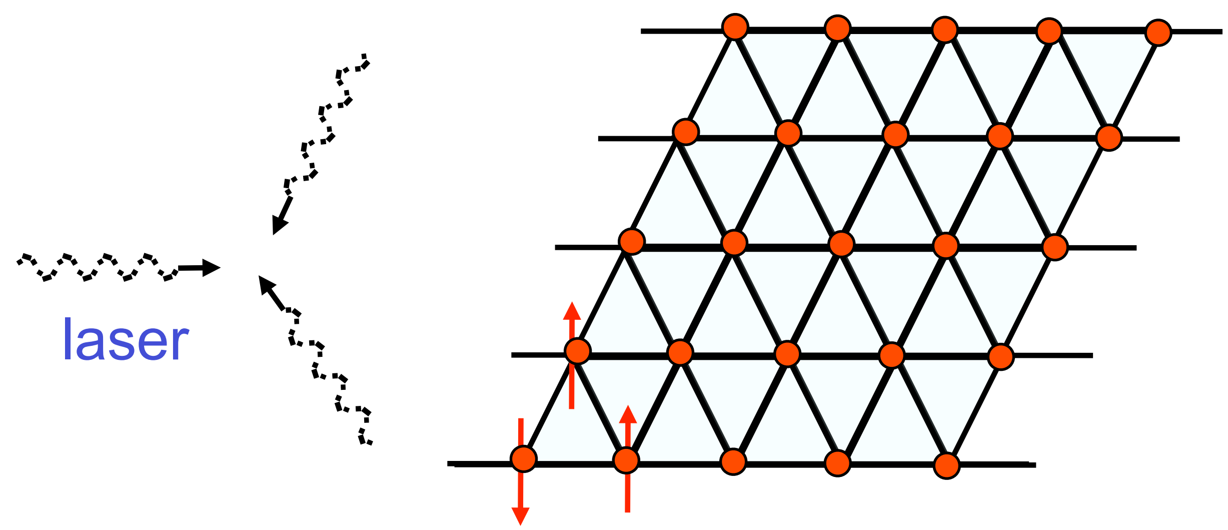
- 1D, 2D and 3D



- lattice configurations

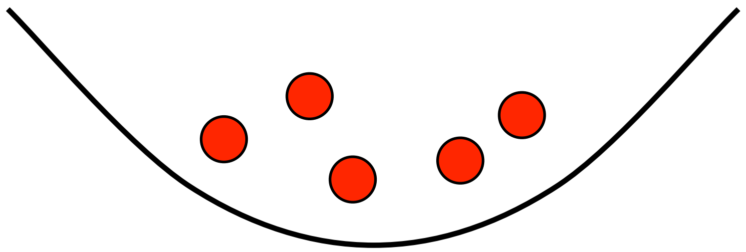


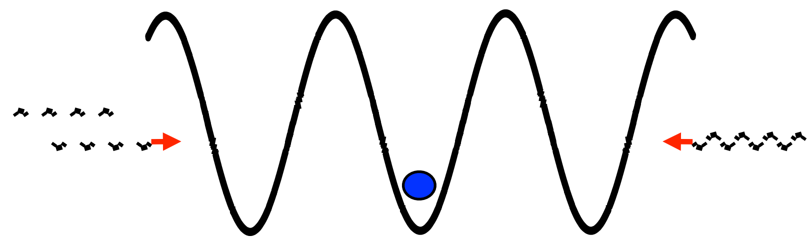
square lattice

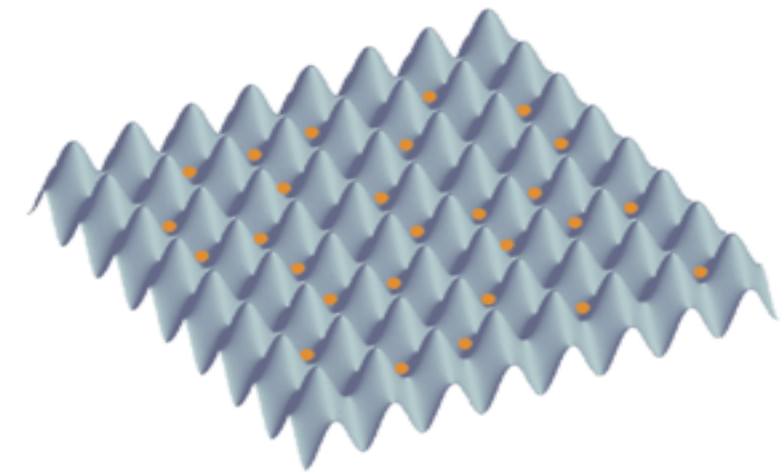


triangular lattice

Atoms in 3D Optical Lattices (also 1D/2D geometries):







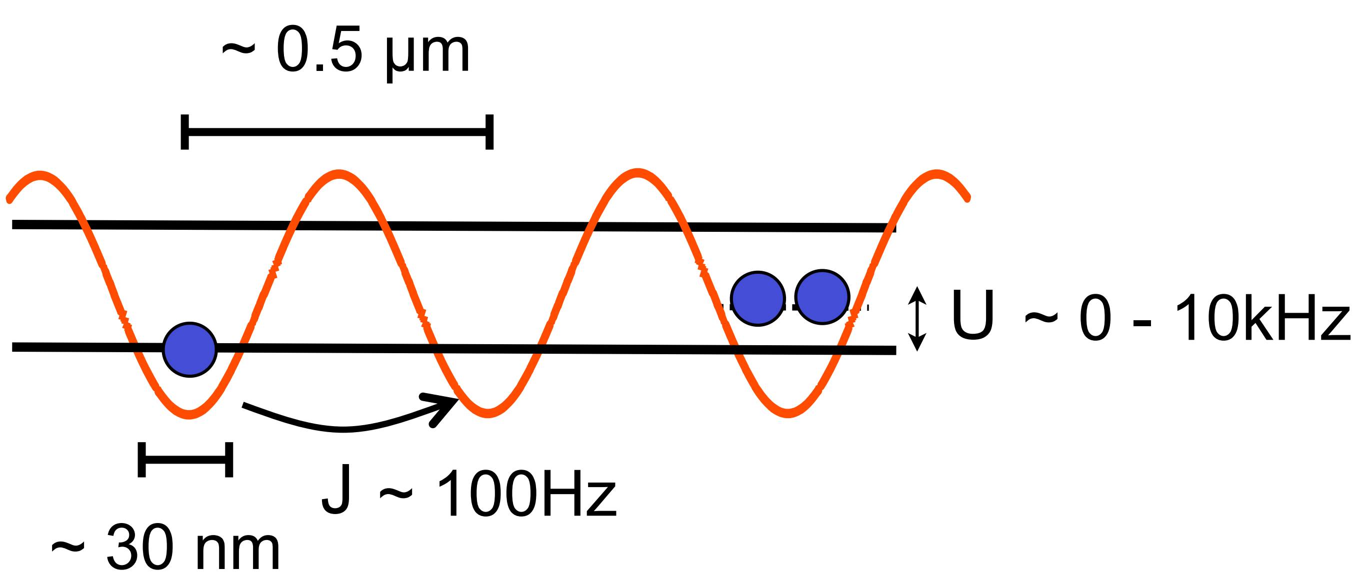
- BEC / degenerate Fermi gas

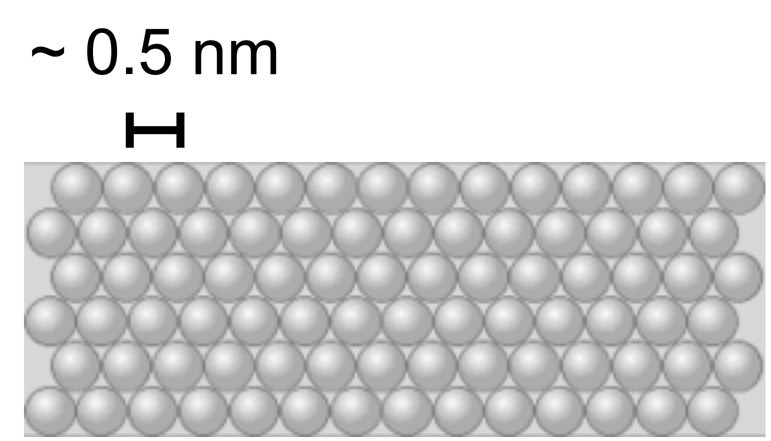
(Weakly interacting)

(Strongly interacting)

- Lattice models (cf. solid state physics)

Bose-Hubbard: D. Jaksch et al. PRL '98





1 kHz = 50 nK

= 4×10^{-12} eV

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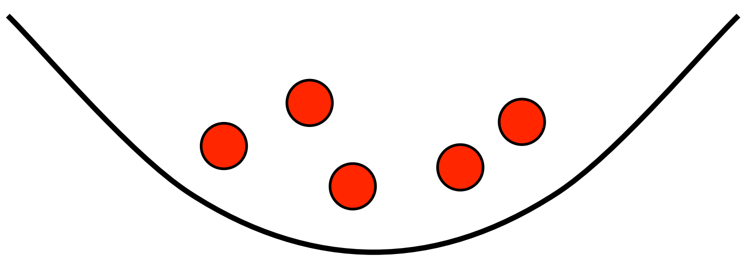
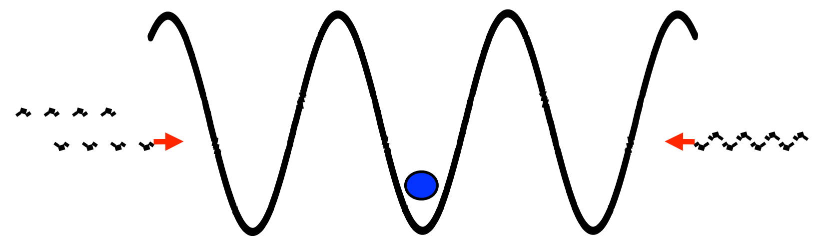
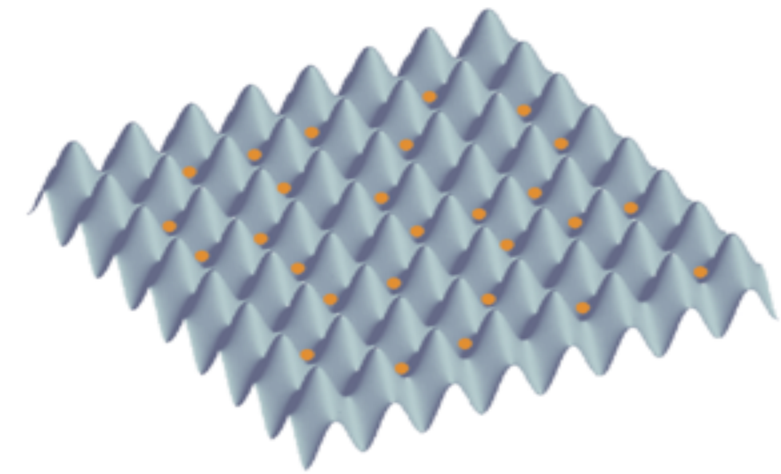






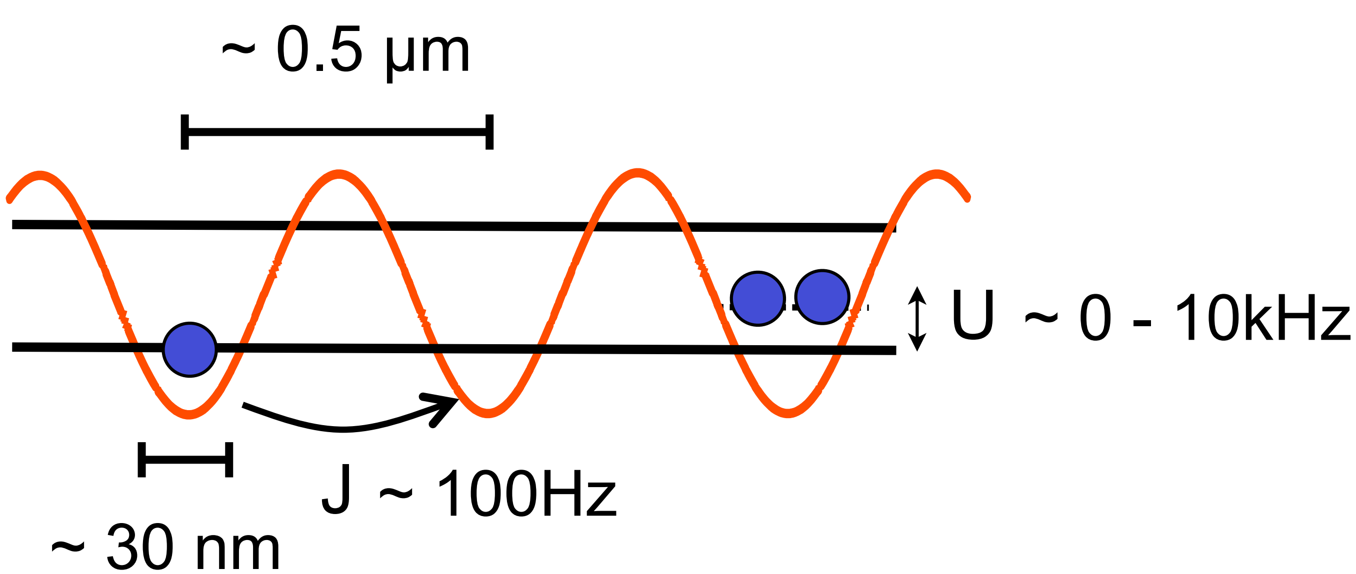
- BEC / degenerate Fermi gas

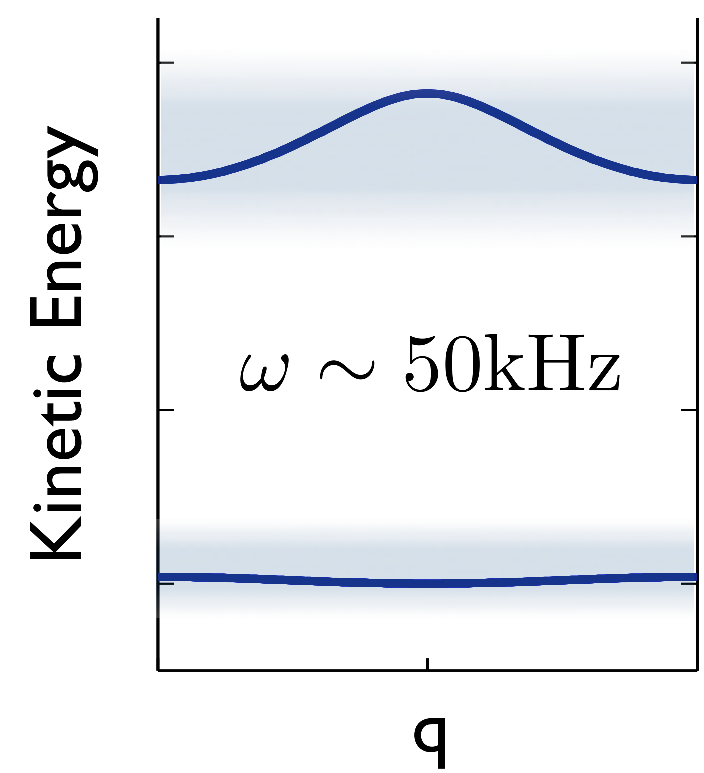
(Weakly interacting)

(Strongly interacting)

- Lattice models (cf. solid state physics)
- Band structure (c.f. electrons)

Bose-Hubbard: D. Jaksch et al. PRL '98





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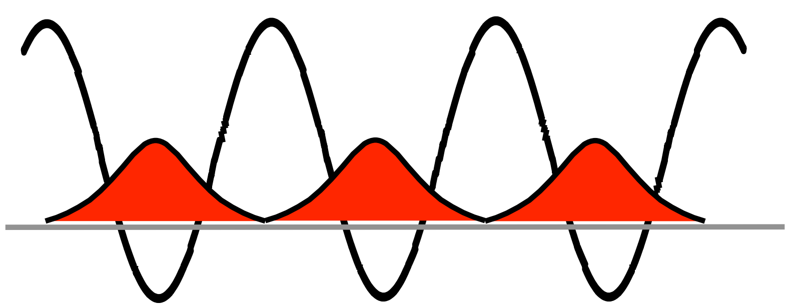
Bose-Hubbard model

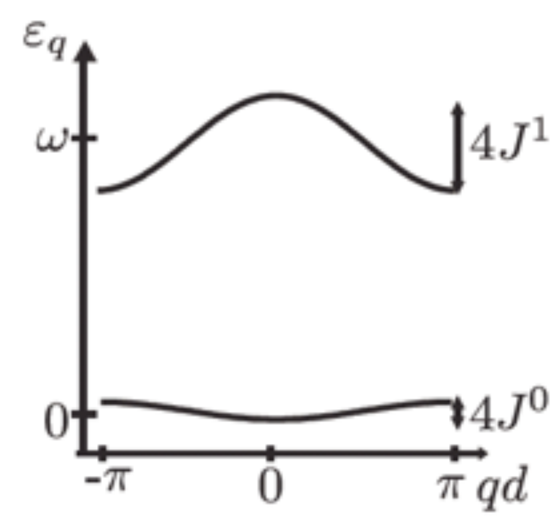
MORE IN TOMORROW'S LECTURE

$$\hat{H} = \int \mathrm{d}\mathbf{x} \hat{\Psi}^\dagger(\mathbf{x}) \left(-\frac{\hbar^2}{2m}\nabla^2 + V(\mathbf{x}) \right) \hat{\Psi}(\mathbf{x}) + \frac{g}{2} \int \mathrm{d}\mathbf{x} \hat{\Psi}^\dagger(\mathbf{x}) \hat{\Psi}^\dagger(\mathbf{x}) \hat{\Psi}(\mathbf{x}) \hat{\Psi}(\mathbf{x})$$



Wannier functions

$$\psi(\vec{x}) = \sum_\alpha w(\vec{x} - \vec{x}_\alpha)\, b_\alpha$$



Assume:
- Only lowest band
- Only nearest neighbour tunneling
- Only onsite interactions

$$J = -\int \mathrm{d}x\, w_0(x) \left(-\frac{\hbar^2}{2m}\nabla^2 + V_0 \sin^2(k_l x) \right) w_0(x-a),$$

$$U = g \int \mathrm{d}\mathbf{x}\, |w_0(\mathbf{x})|^4,$$

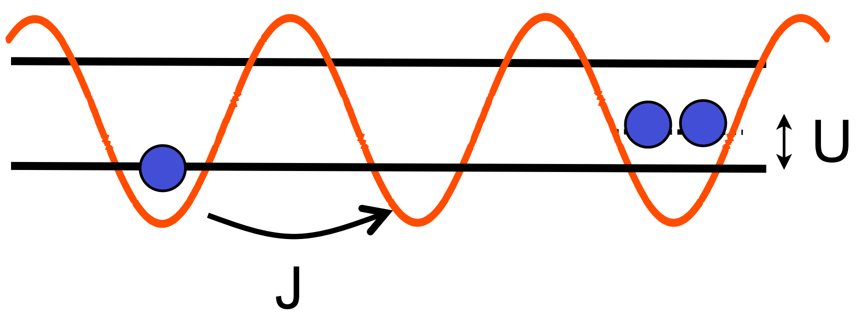
$$\epsilon_i = \int \mathrm{d}\mathbf{x}\, |w_0(\mathbf{x}-\mathbf{x}_i)|^2 \left(V(\mathbf{x}-\mathbf{x}_i) \right),$$

$$\longrightarrow \quad H = -J \sum_{\langle i,j \rangle} \hat{b}_i^\dagger \hat{b}_j + \sum_i \epsilon_i \hat{n}_i + \frac{U}{2} \sum_i \hat{n}_i(\hat{n}_i - 1) \qquad k_B T, J, U \ll \hbar\omega$$

D. Jaksch, C. Bruder, J. I. Cirac, C. W. Gardiner, and P. Zoller, Phys Rev. Lett. **81**, 3108 (1998)

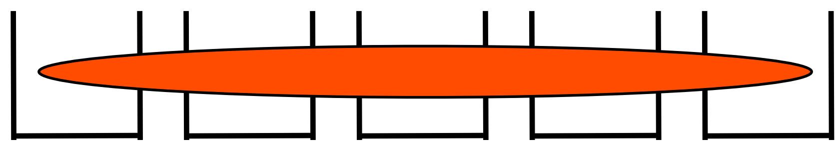
E.g., Bose-Hubbard model:

D. Jaksch et al., PRL '98
M. Greiner et al., Nature '02

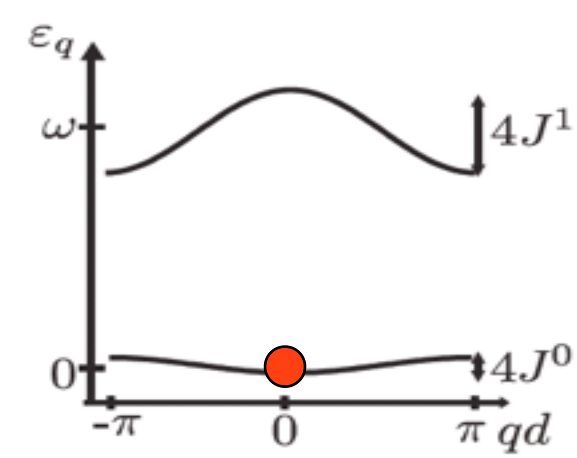


$$\hat{H} = -J \sum_{\langle i,j \rangle} b_i^\dagger b_j + \frac{U}{2} \sum_i \hat{n}_i(\hat{n}_i - 1)$$

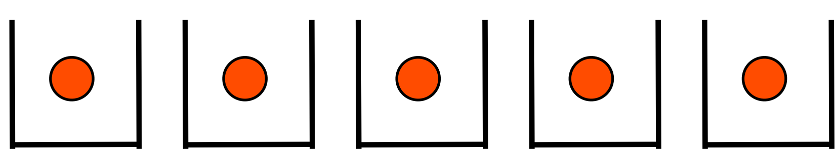
- **Superfluid** J>>U



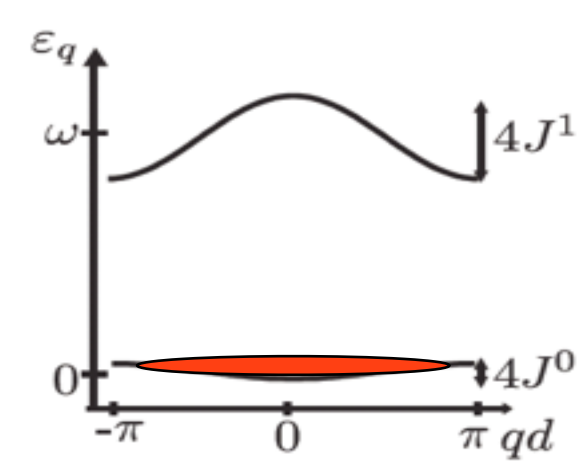
Delocalised atoms: BEC



- **Mott Insulator Phase:** J<<U

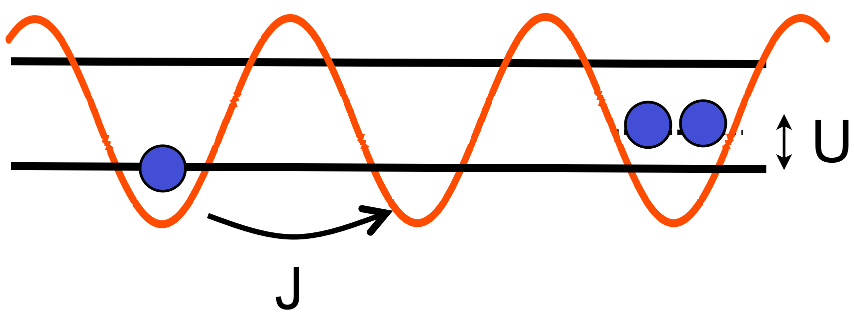


commensurate filling: atoms
"pinned" by interactions



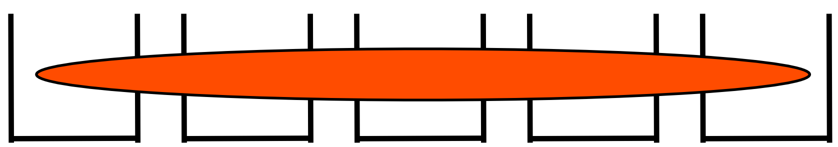
Bose-Hubbard model

D. Jaksch et al., PRL ’98
M. Greiner et al., Nature ’02



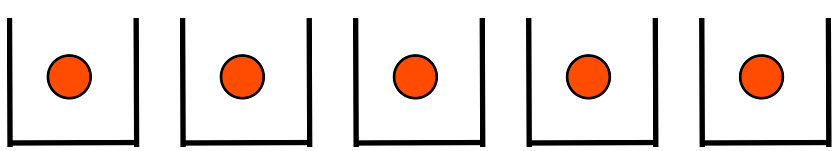
$$\hat{H} = -J \sum_{\langle i,j \rangle} b_i^\dagger b_j + \frac{U}{2} \sum_i \hat{n}_i(\hat{n}_i - 1)$$

- **Superfluid** J>>U



Delocalised atoms: BEC

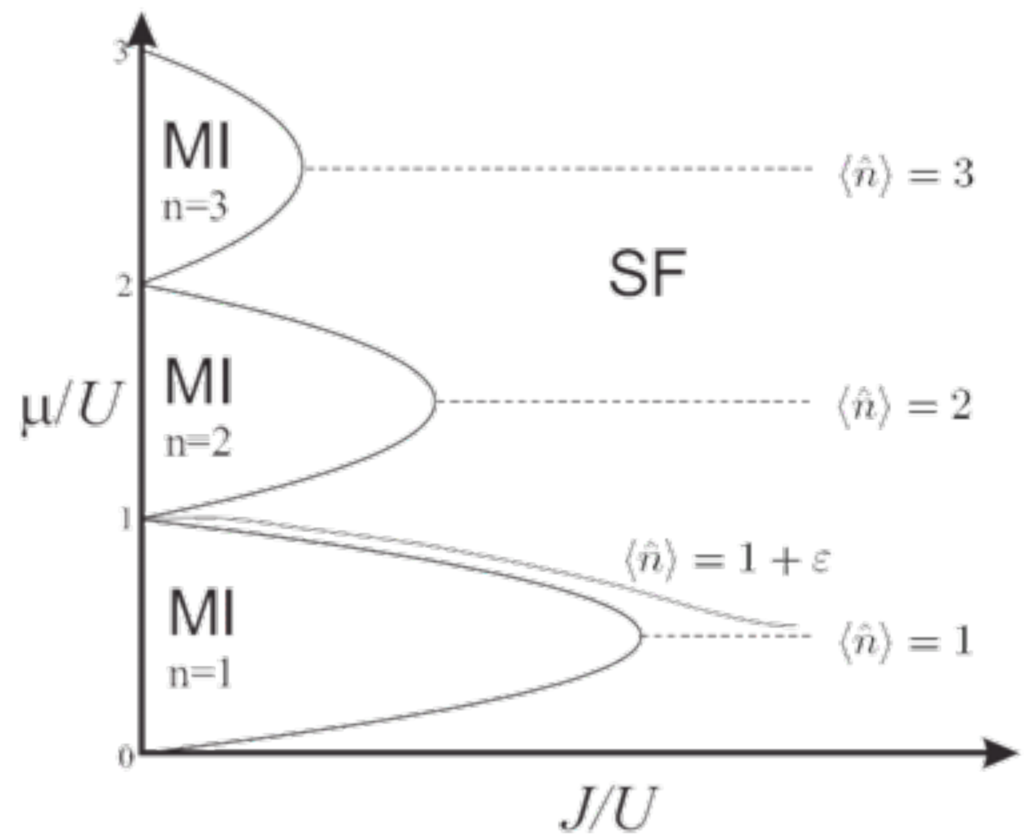
- **Mott Insulator Phase:** J<<U



commensurate filling: atoms “pinned” by interactions

- Microscopic understanding
- Time-dependent parameter control
- Large size (μm), long lifetime (s)

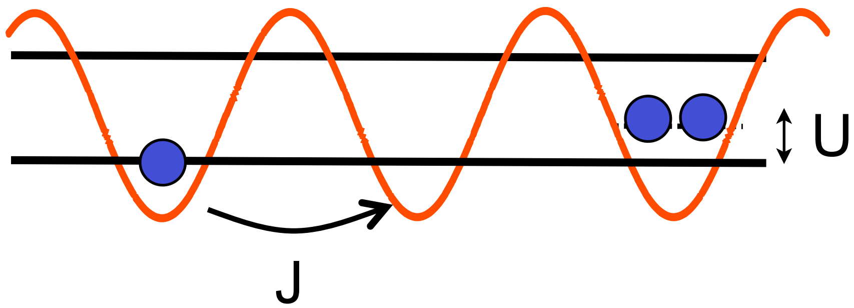
- **Phase Diagram** (U>0)



Experiments:
Munich, Zurich, NIST / JQI, MIT, Harvard, Innsbruck, Hamburg, Pisa, Florence, Oxford, Cambridge, Austin, Chicago, Penn State, Kyoto, Toronto, Stony Brook, Paris, Strathclyde, Illinois, Cornell......

Observation via momentum distribution

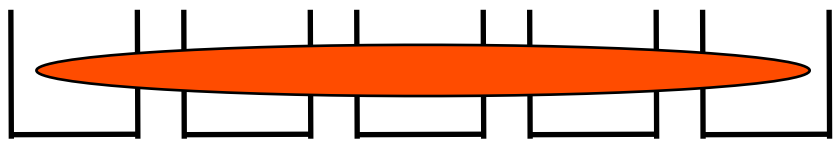
D. Jaksch et al., PRL '98
M. Greiner et al., Nature '02



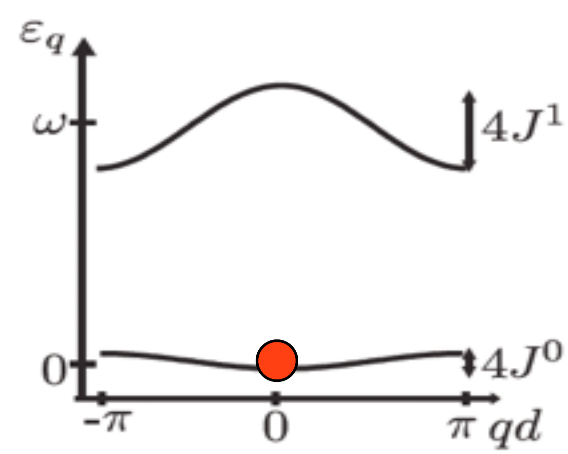
$$\hat{H} = -J \sum_{\langle i,j \rangle} b_i^\dagger b_j + \frac{U}{2} \sum_i \hat{n}_i(\hat{n}_i - 1)$$

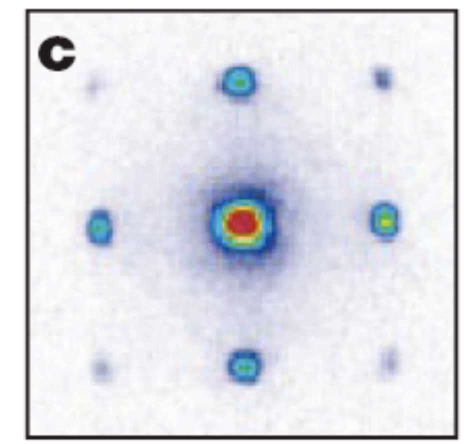
Momentum Distribution

- **Superfluid** J>>U

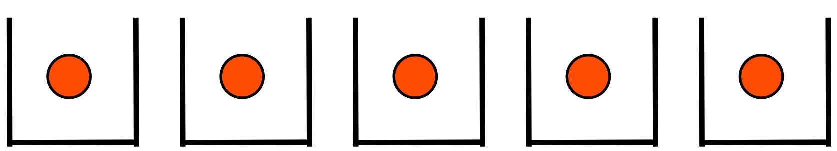


Delocalised atoms: BEC

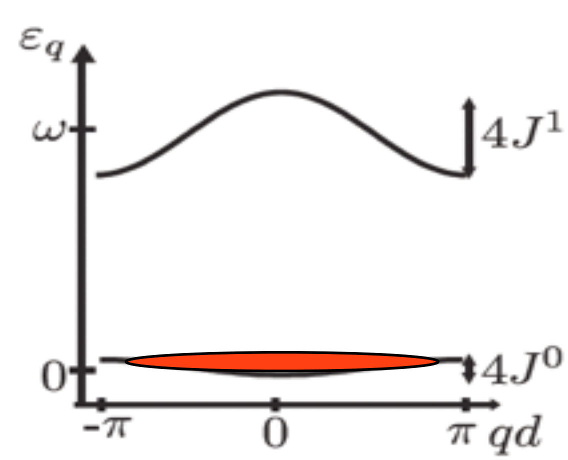


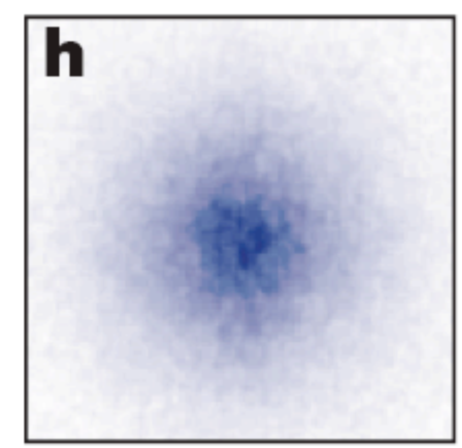


- **Mott Insulator Phase:** J<<U



commensurate filling: atoms "pinned" by interactions





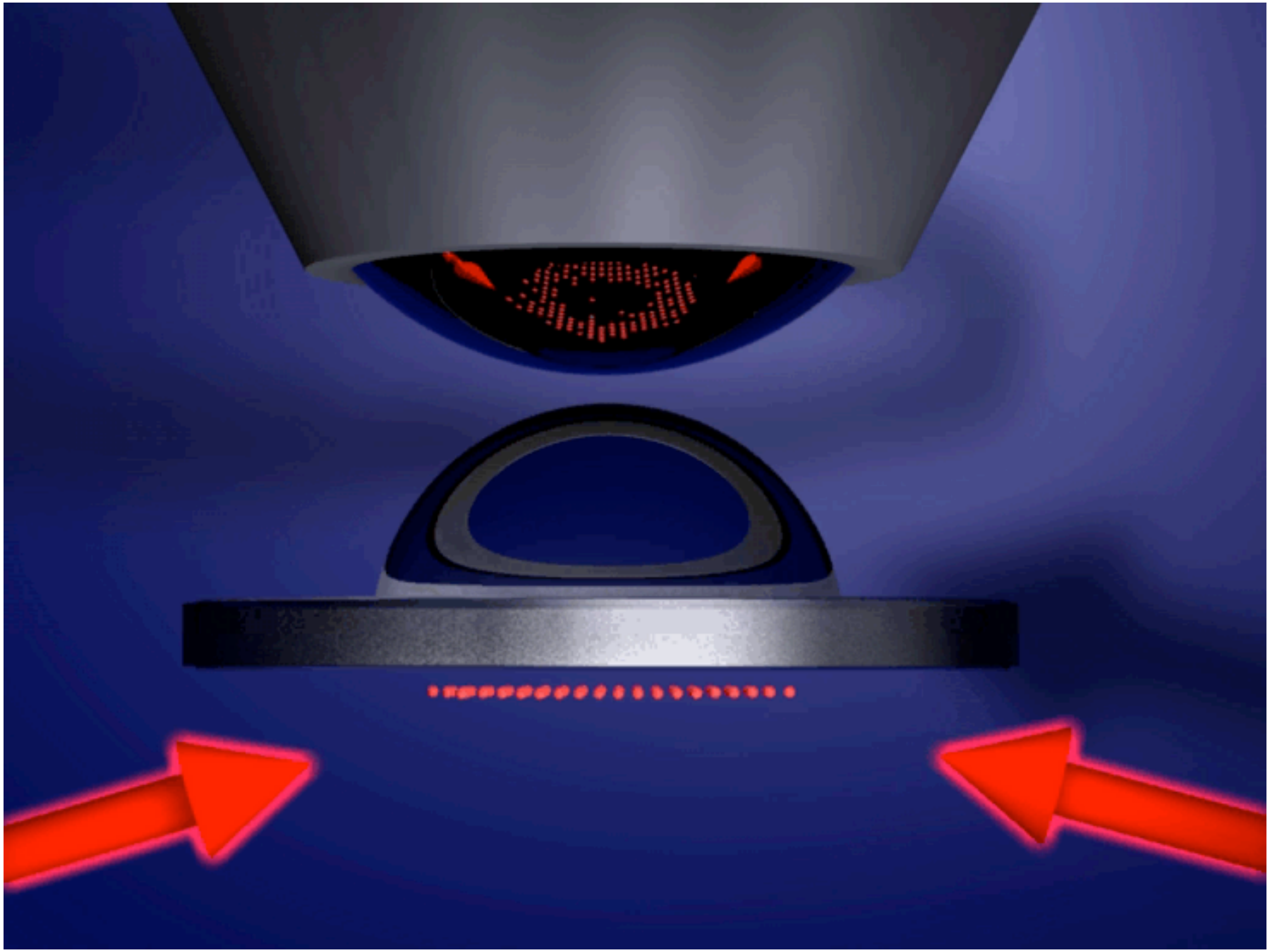
M. Greiner et al., Nature '02

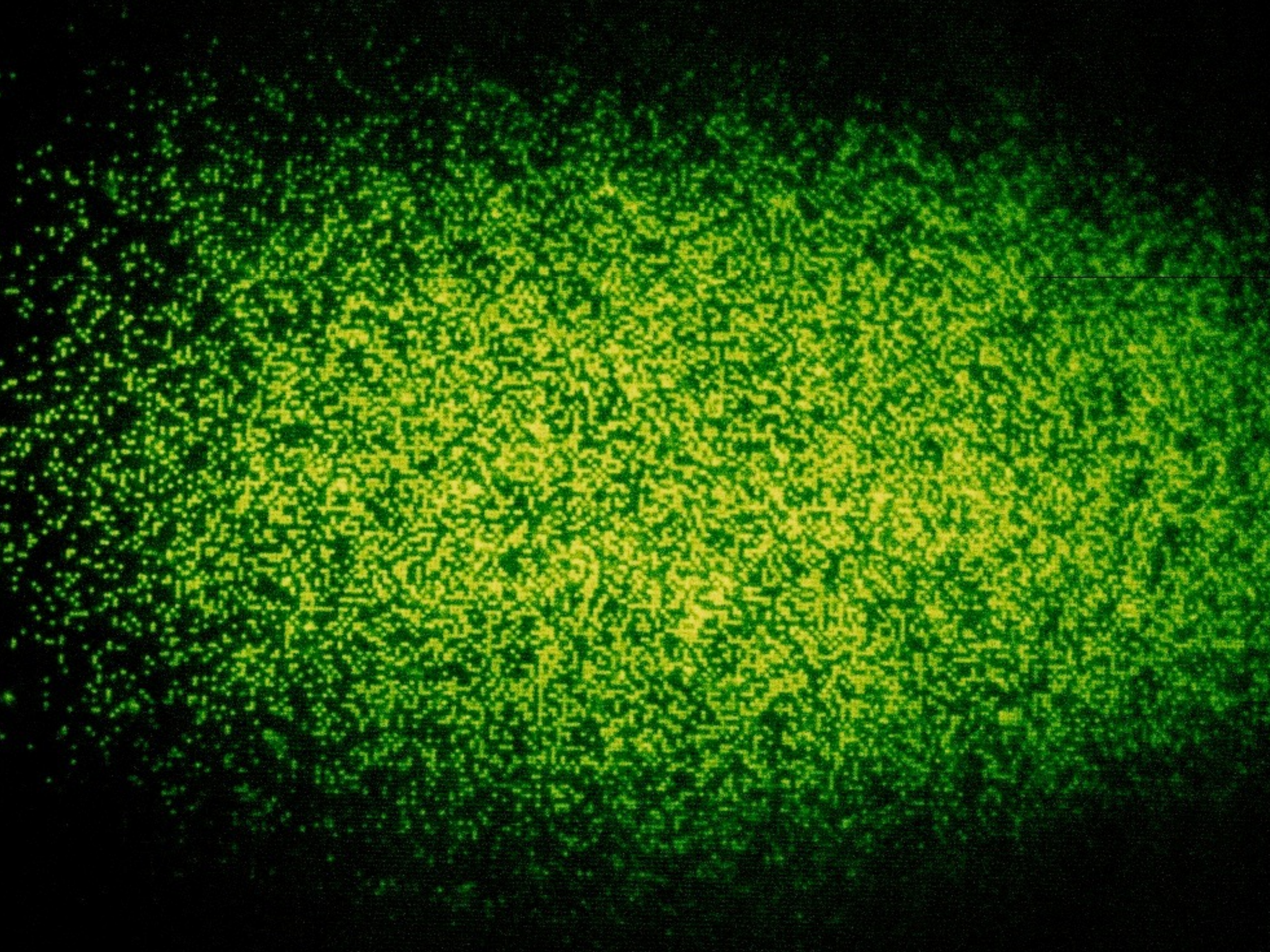
Overview of Quantum Simulation

- Analogue and digital quantum simulators
- Microscopic description of cold atomic gases
- Example: The Bose-Hubbard Model
- Recent developments and extensions
- Perspectives

New Possibility: In-situ measurement of atoms, correlation functions:

- Experiments: Harvard, Munich, Strathclyde, Chicago, Oxford, Toronto, MIT.....
- e.g., Markus Greiner's "Microscope" at Harvard:



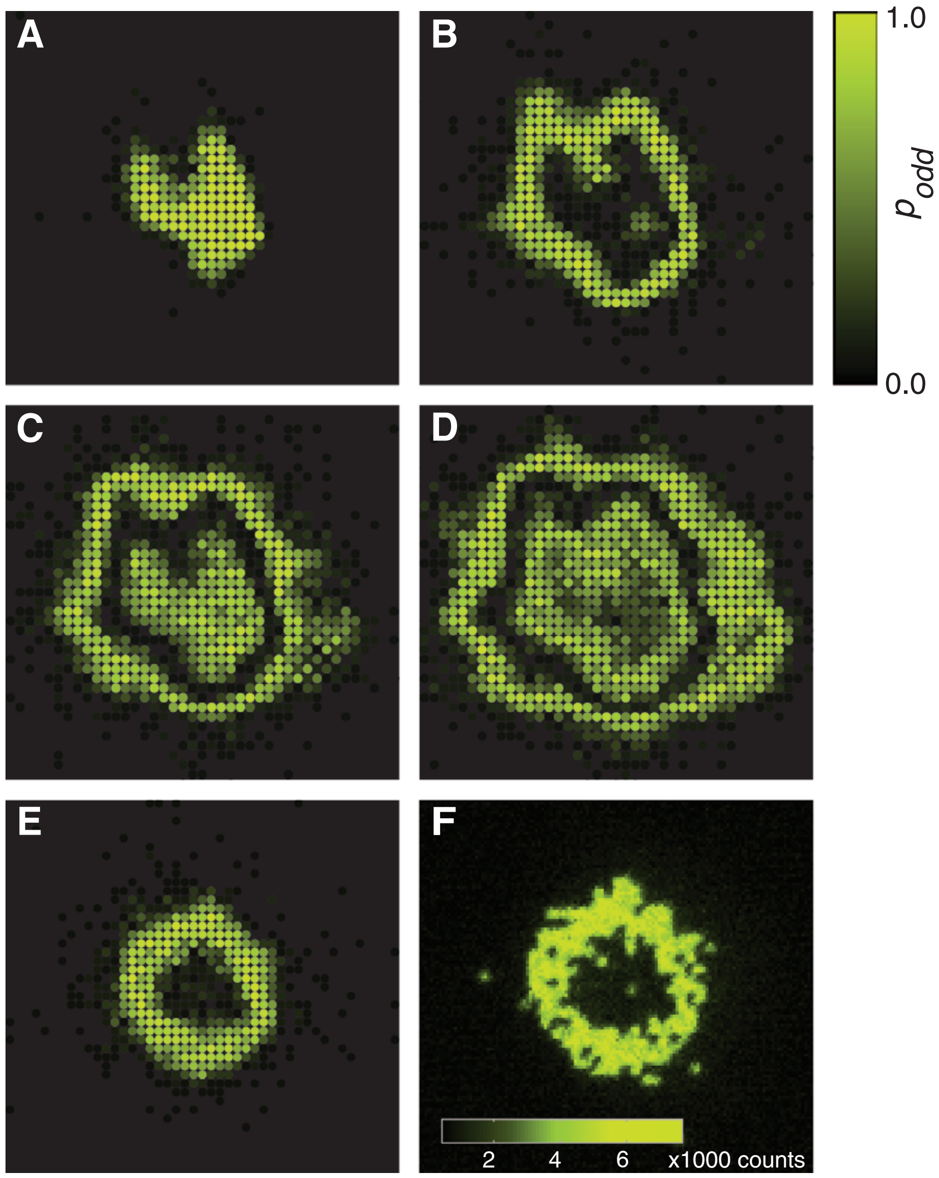


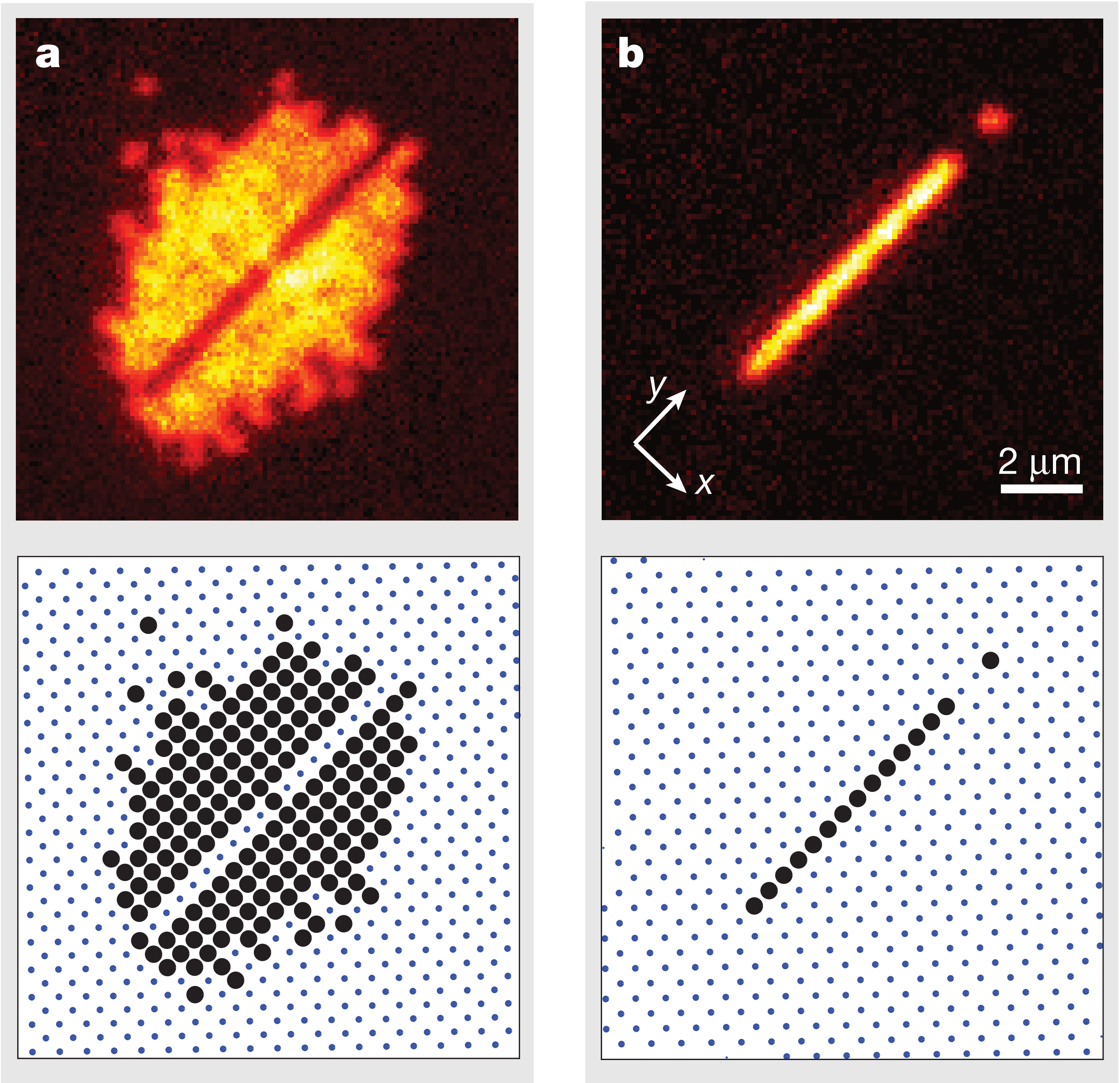
New Possibility: In-situ measurement of atoms, correlation functions:

- Experiments: Harvard, Chicago, Munich, Oxford, Toronto, Strathclyde, MIT…..
- "Quantum Gas Microscopes" at Harvard / Garching:

W. S. Bakr, A. Peng, M. E. Tai, R. Ma, J. Simon, J. I. Gillen, S. Foelling, L. Pollet, and M. Greiner, Science 329, 547-550 (2010).

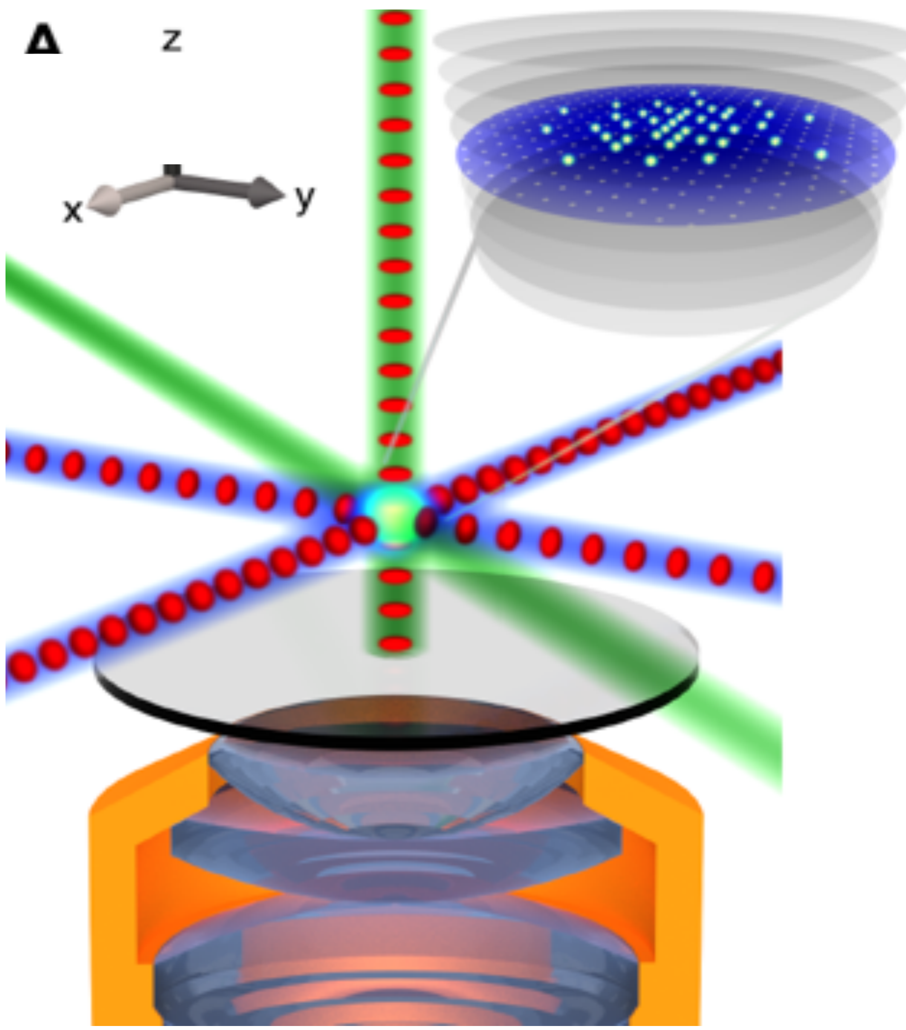
C. Weitenberg, M. Endres, J. F. Sherson, M. Cheneau, P. Schauß, T. Fukuhara, I. Bloch, and S. Kuhr, Nature 471, 319-324 (2011).

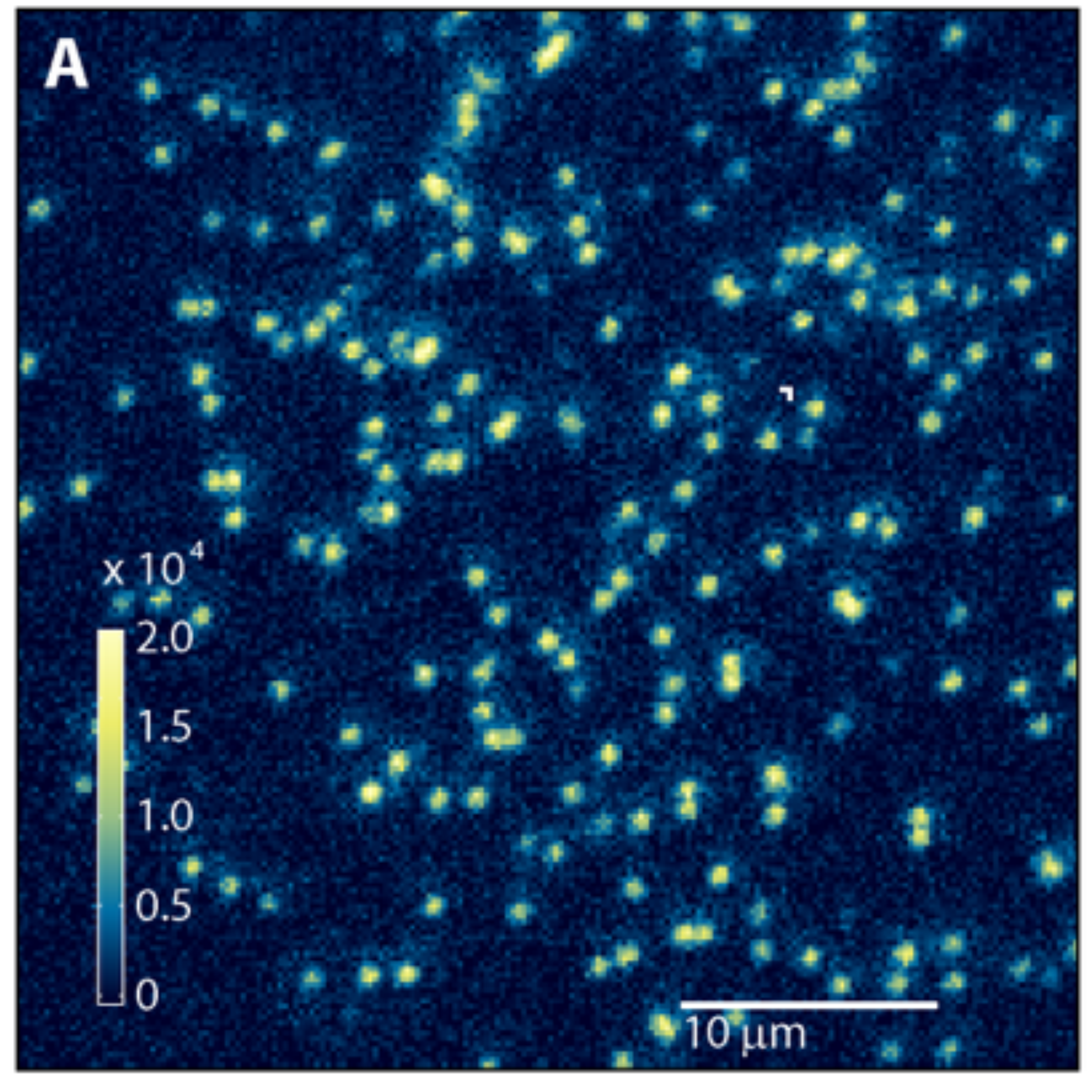




Quantum Particles
Put Under the Microscope

First images of individual fermionic atoms (March 2015)





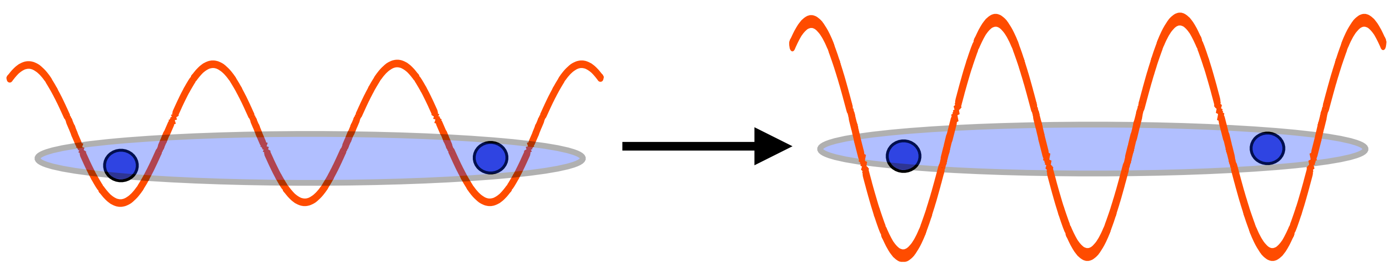
1.5 s exposure time

Stefan Kuhr & Team, University of Strathclyde, Glasgow, UK

Elmar Haller, Stefan Kuhr et al., Nature Physics **11**, 738 (2015)

Coherent non-equilibrium dynamics:

- Intrinsic interest, e.g., Quench dynamics, thermalization, entanglement growth



M. Greiner *et al.*, Nature **419**, 51 (2002).
S. Will *et al.*, Nature **465**, 197 (2010).

M. Cheneau *et al.*, Nature **481**, 484 (2012)
J.-S. Bernier *et al.*, PRL **106**, 200601 (2011)

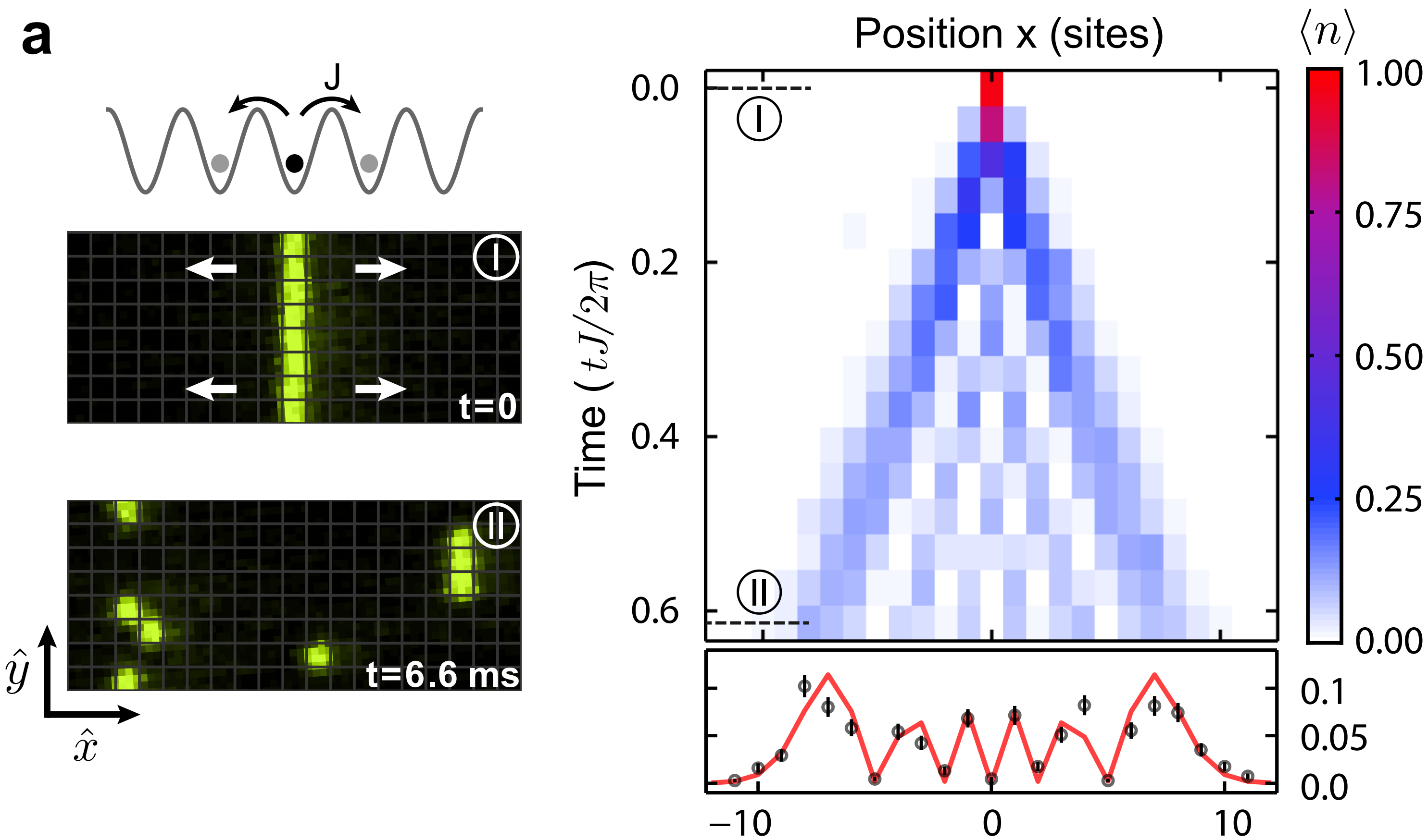
- Millisecond timescales - track+control in real time
- Long coherence times; isolated system

Calabrese, Cardy, Essler, Olshanii, Rigol,……

- Computations in 1D with time-dependent DMRG

Läuchli, Kollath, Heidrich-Meissner,
Schollwöck, White, ……

Quantum walks in optical lattices with quantum gas microscopes

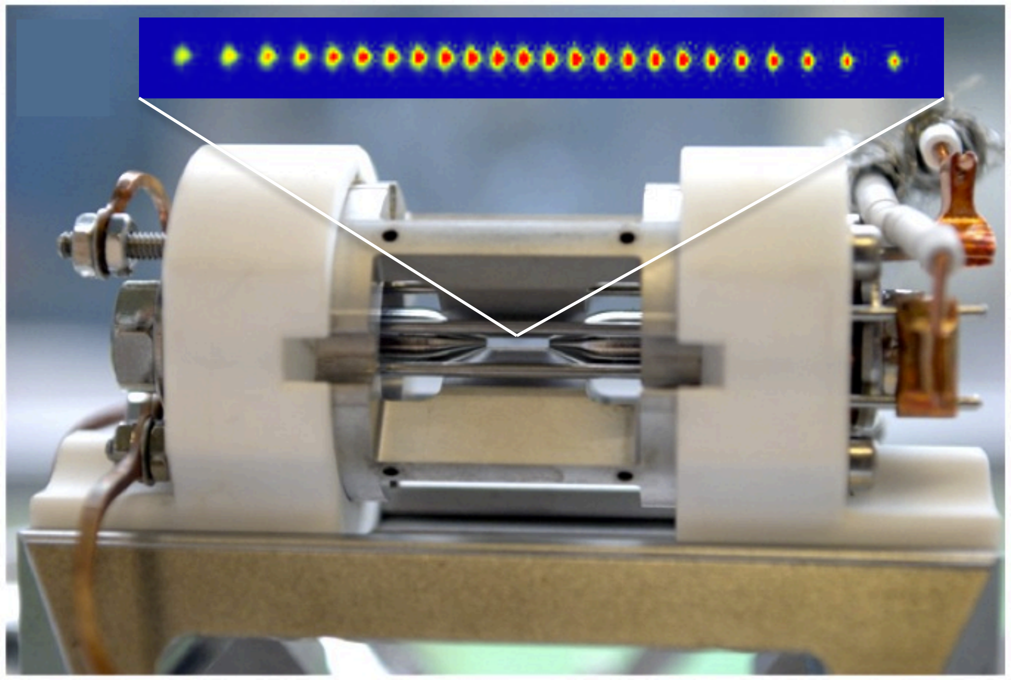


- Initial state: chain of atoms
- Quantum random walk

P. M. Preiss et al., Science **347**, 1229 (2015)

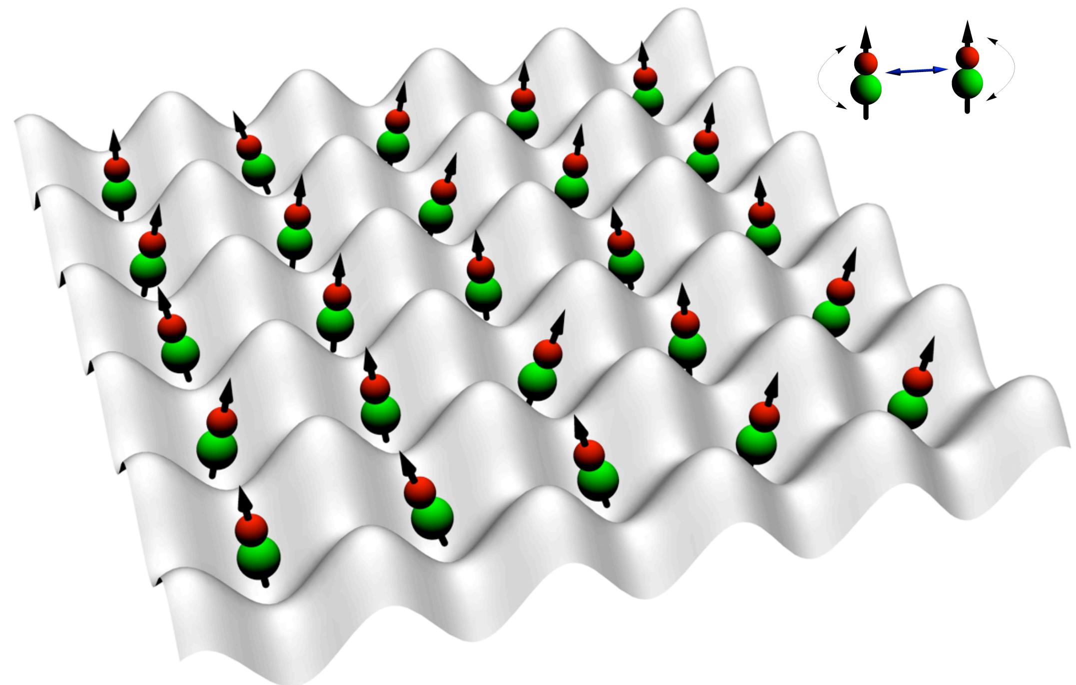
Long-range interactions in quantum simulators:

Trapped ions



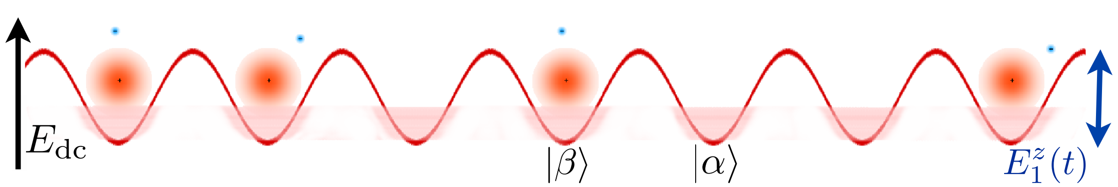
R D. Porras, J. I. Cirac, PRL 92, 207901 (2004)
R. Islam et al, Science, 340, 583 (2013)
JW Britton et al. Nature 484, 489 (2012)
P. Jurcevic et al., arXiv:1401.5387

Polar Molecules



A. Micheli et al., Nature Phys. 2, 341 (2006)
B. Yan et al., Nature 501, 521(2013)

Rydberg atoms

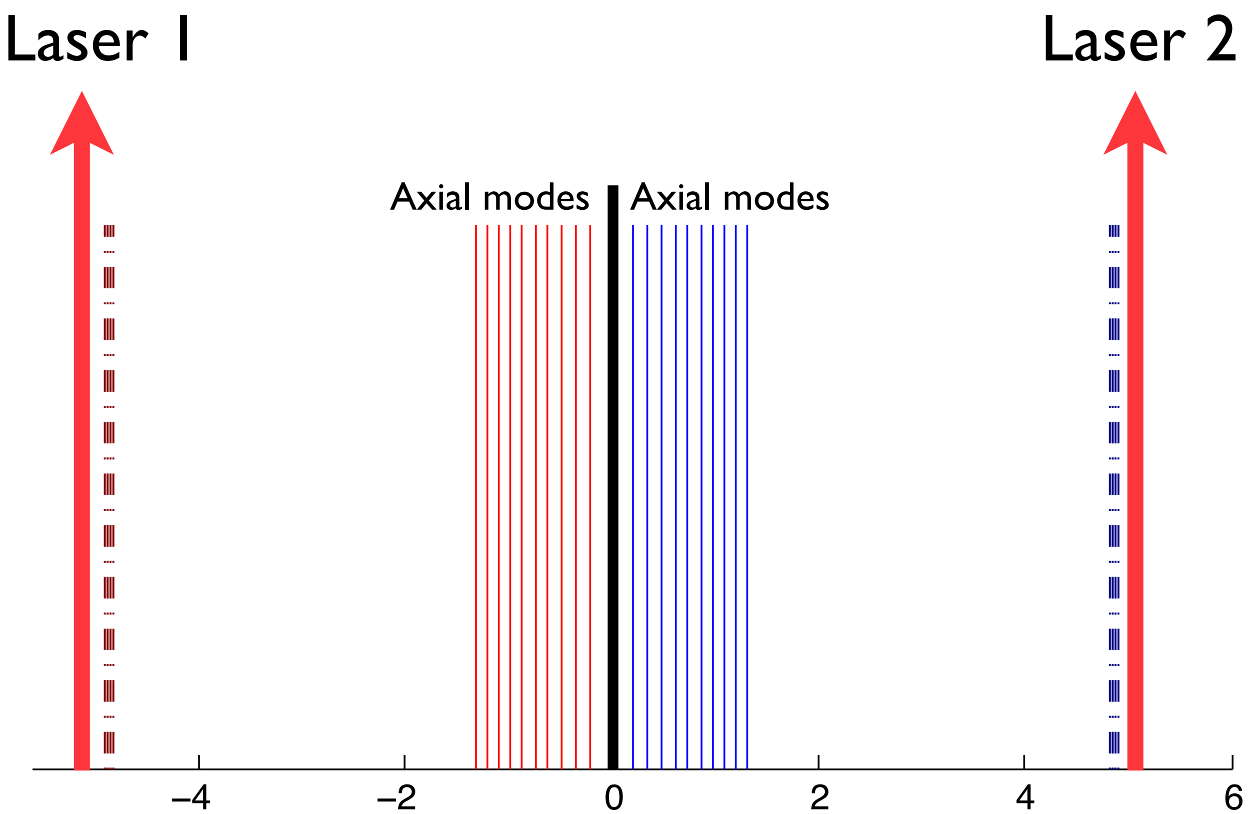


Expts: Stuttgart, Wisconsin, Orsay, Munich, Pisa…

- Novel quantum phases
- Novel state preparation methods
- Out of equilibrium dynamics:
  Quenches?

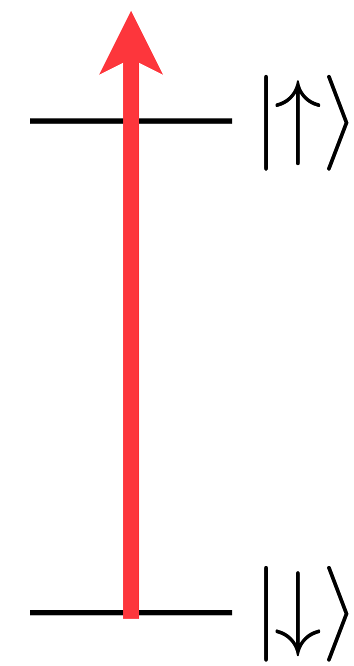
Tuneable-range interactions in ion traps:

State-dependent-force that off resonantly drives many modes at once



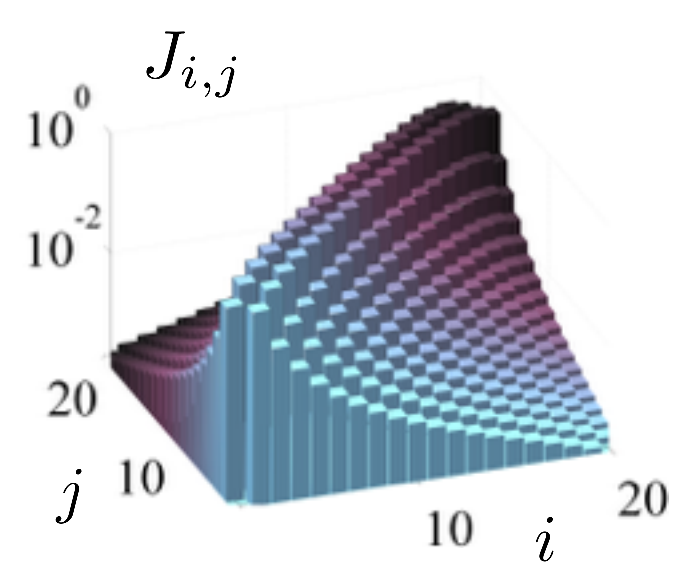
$$H = \sum_{i,j} J_{ij} \sigma_i^x \sigma_j^x$$

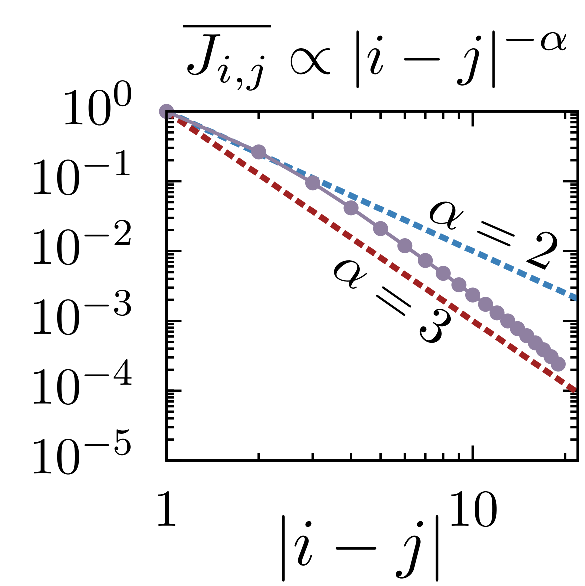
$$J_{ij} \sim \frac{1}{|i-j|^{\alpha}} \qquad 0 \le \alpha \le 3$$



- Range determined by detuning (how equal coupling is to all modes)
- Addition control varying axial confinement
- Long strings, hot axial modes

A. Sørensen and K. Mølmer, PRA 62, 022311 (2000)
D. Porras, J. I. Cirac, Phys. Rev. Lett. 92, 207901 (2004)
R. Islam et al, Science, 340, 583 (2013)
JW Britton et al. Nature 484, 489 (2012)





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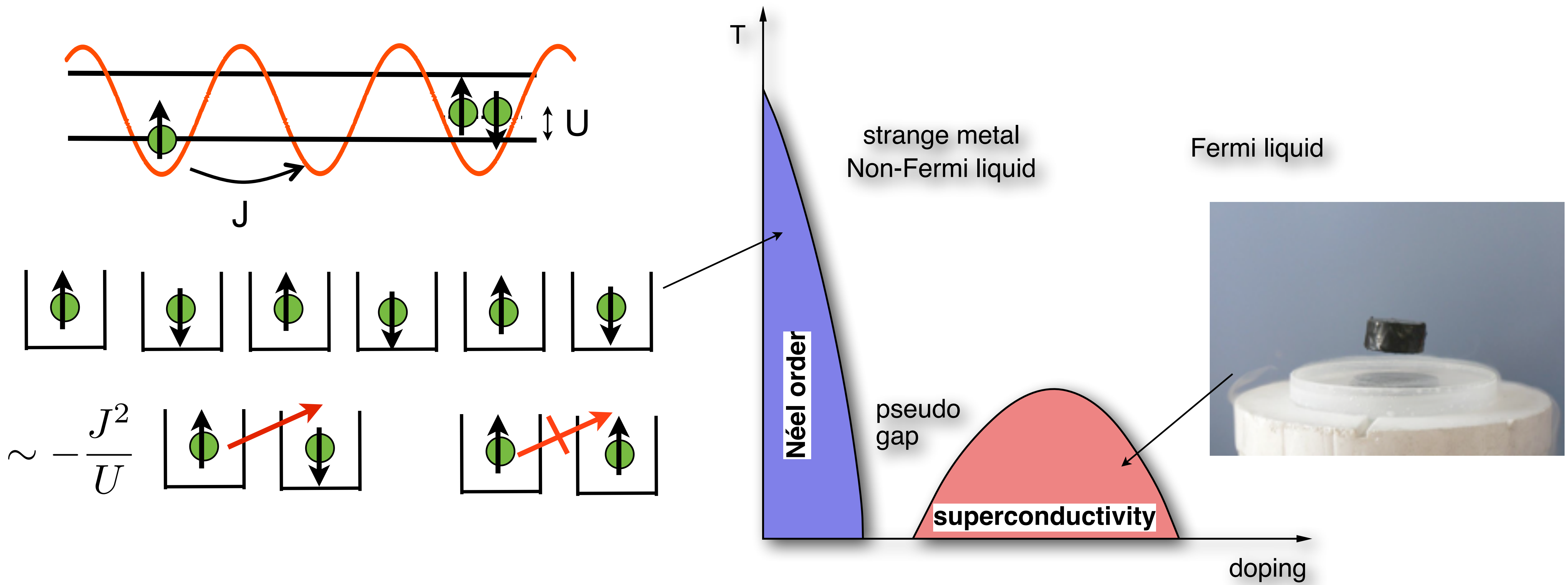
“Quantum Simulation”:

e.g., Relationship to high Tc superconductivity of cuprates - two-species experiments:



Simulations:

- Study models where we can’t access physics via classical computations
- e.g., materials engineering

Real matter; new quantum phases

- Realise interesting many-body physics predicted but not yet observed in experiments
- Also: Exotic phases, spin models, simulators for graphene, disorder, impurities,.......

Current challenges: cooling, state preparation, control over heating in lattices

A desiderata for quantum simulation

CIRAC & ZOLLER QUANTUM SIMULATOR CRITERIA

1. **Quantum system:** A quantum simulator should possess a system of bosons or/and fermions. The system should contain a large number of degrees of freedom.

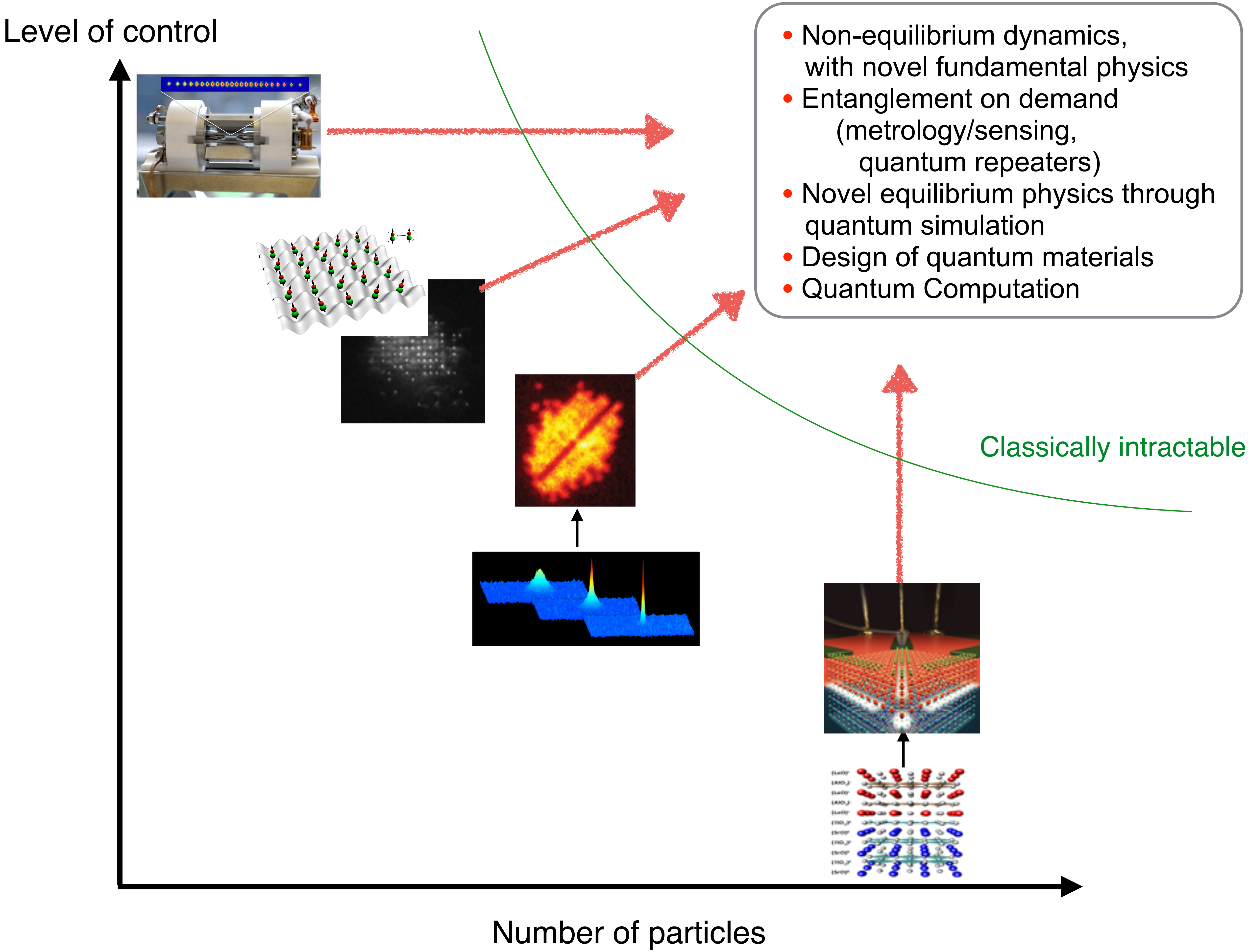
2. **Initialization:** A quantum simulator should be able to prepare (approximately) a known quantum state.

3. **Hamiltonian engineering:** It should be possible to engineer a set of interactions with external fields or between different particles, with adjustable values.

4. **Detection:** One should be able to perform measurements on the system. This could be individual (addressing a single/few site(s) on the lattice) or collective.

5. **Verification:** Although by definition there should be no way of verifying if the result of the simulation is correct, there should be a way of increasing the confidence in the result.

J.I. Cirac and P. Zoller, *Goals and opportunities in quantum simulation*, Nature Physics 8 (2012), pp. 264–266.


Level of control
Number of particles
• Non-equilibrium dynamics,
with novel fundamental physics
• Entanglement on demand
(metrology/sensing,
quantum repeaters)
• Novel equilibrium physics through
quantum simulation
• Design of quantum materials
• Quantum Computation
Classically intractable