# Simulating Quantum Dynamics in an Optical Lattice

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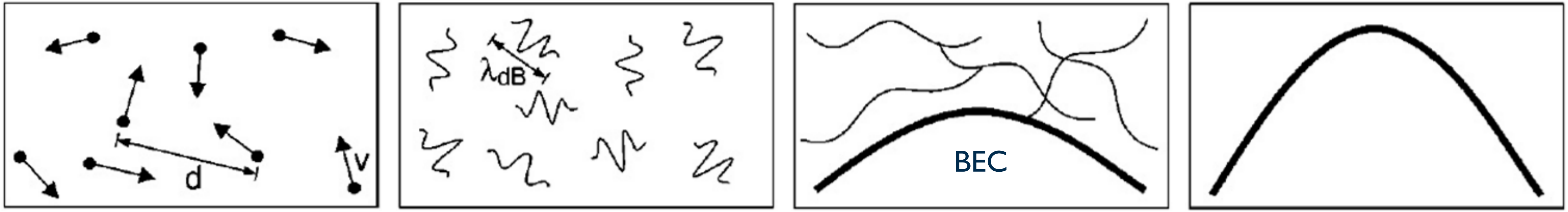
# Bose-Einstein condensates (BEC)s

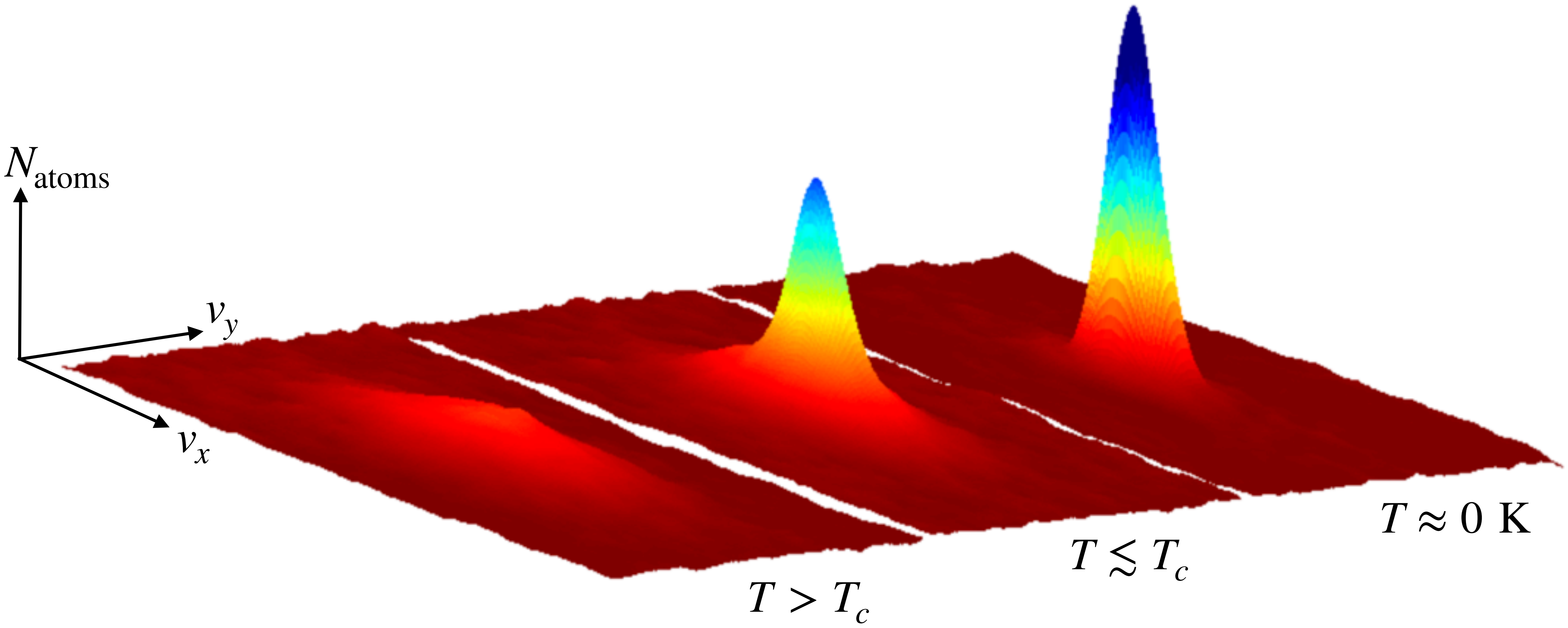



$T \gg T_c$ $T > T_c$ $T \lesssim T_c$ $T \approx 0\ \text{K}$

$$\lambda_{dB} = \sqrt{\frac{h}{2\pi mkT}}$$

BEC formation, figure from Stefan Kienzle talk, 22 May 2013.

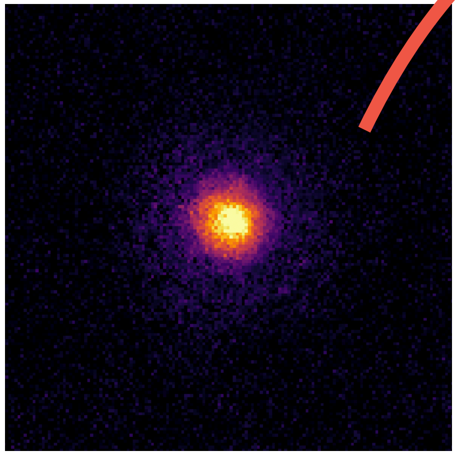
# Strontium BEC at UCSB

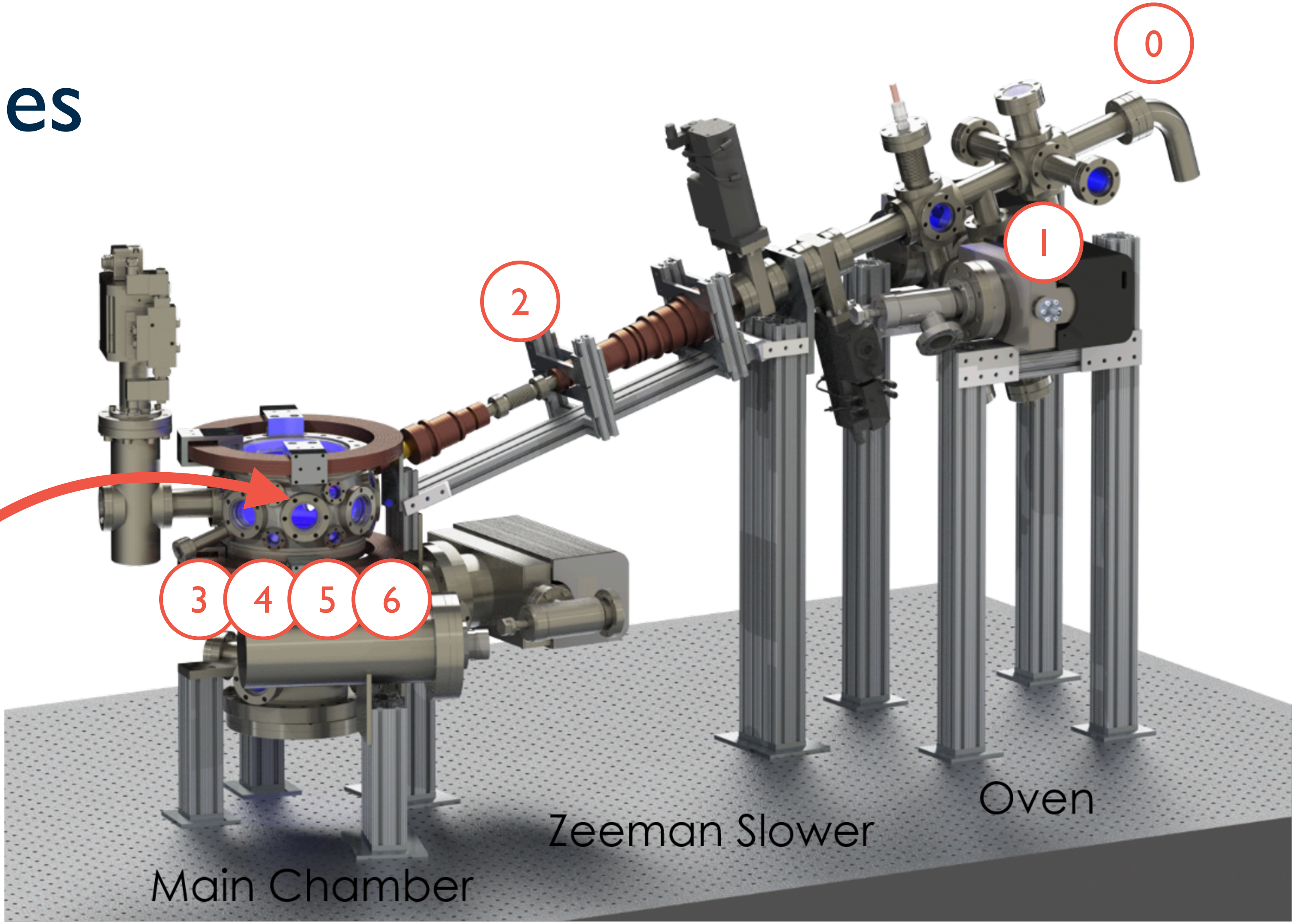



Strontium BEC, image from Weld Lab.

# Cooling phases

0. Atomic oven
1. Transverse cooling
2. Zeeman slower
3. Blue MOT
4. Stable magnetic trap
5. Red MOT
6. Evaporative cooling

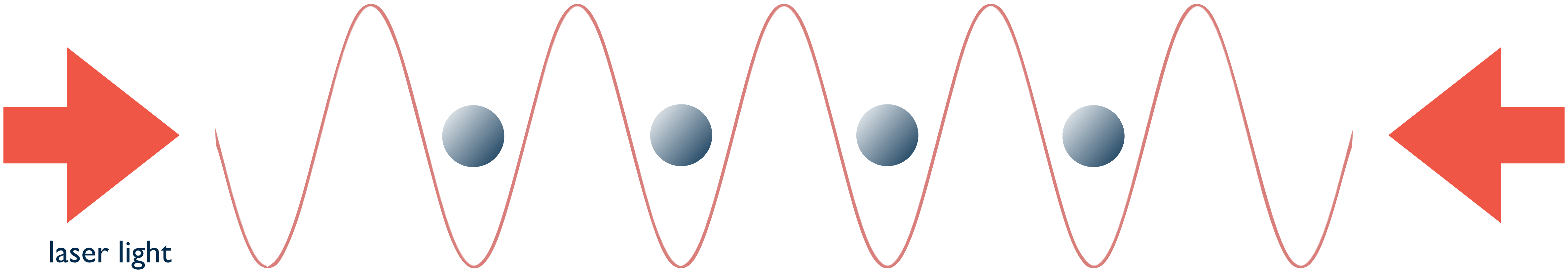




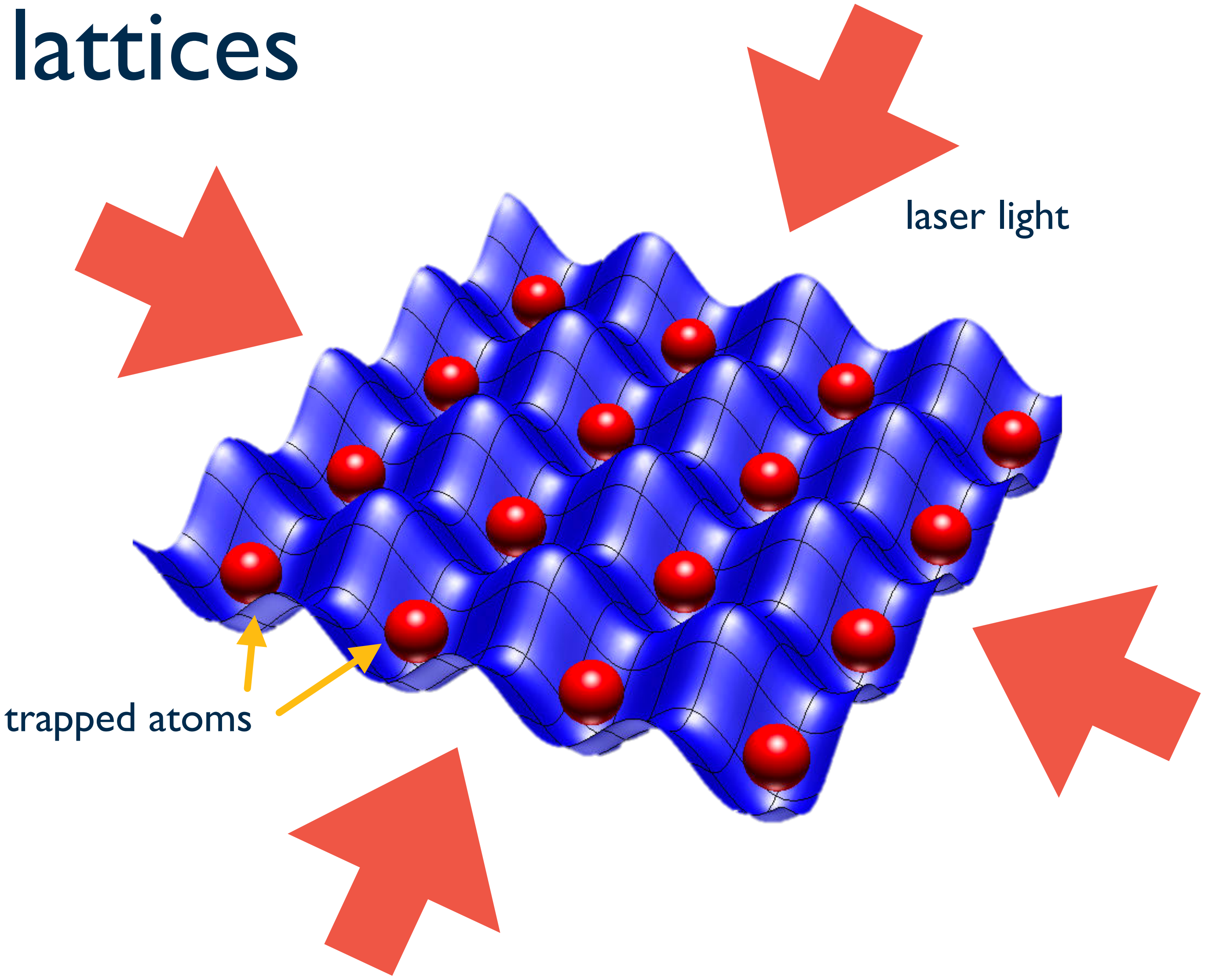

Strontium BEC, figure from Senaratne thesis.

Strontium BEC machine, figure from Rajagopal thesis.

# Optical lattices

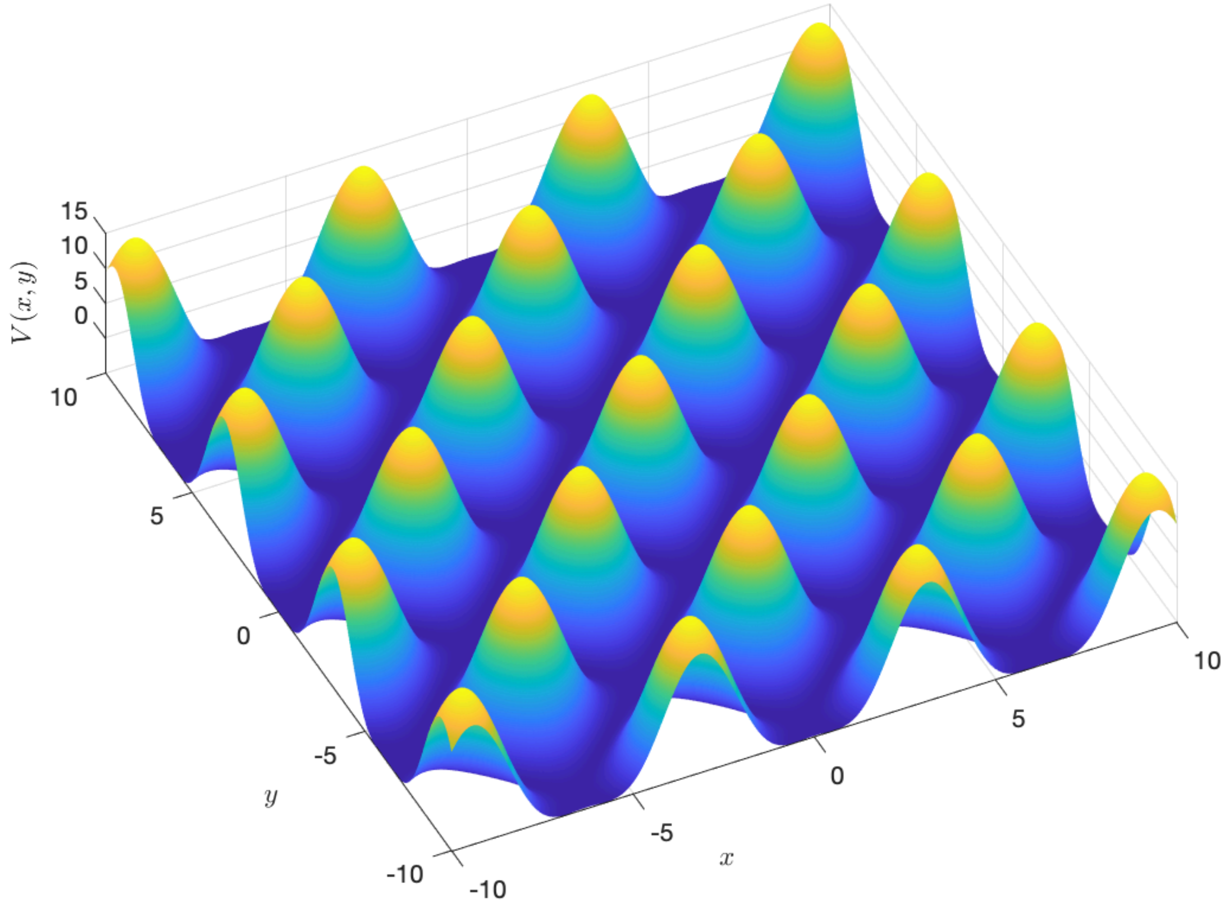


# Optical lattices

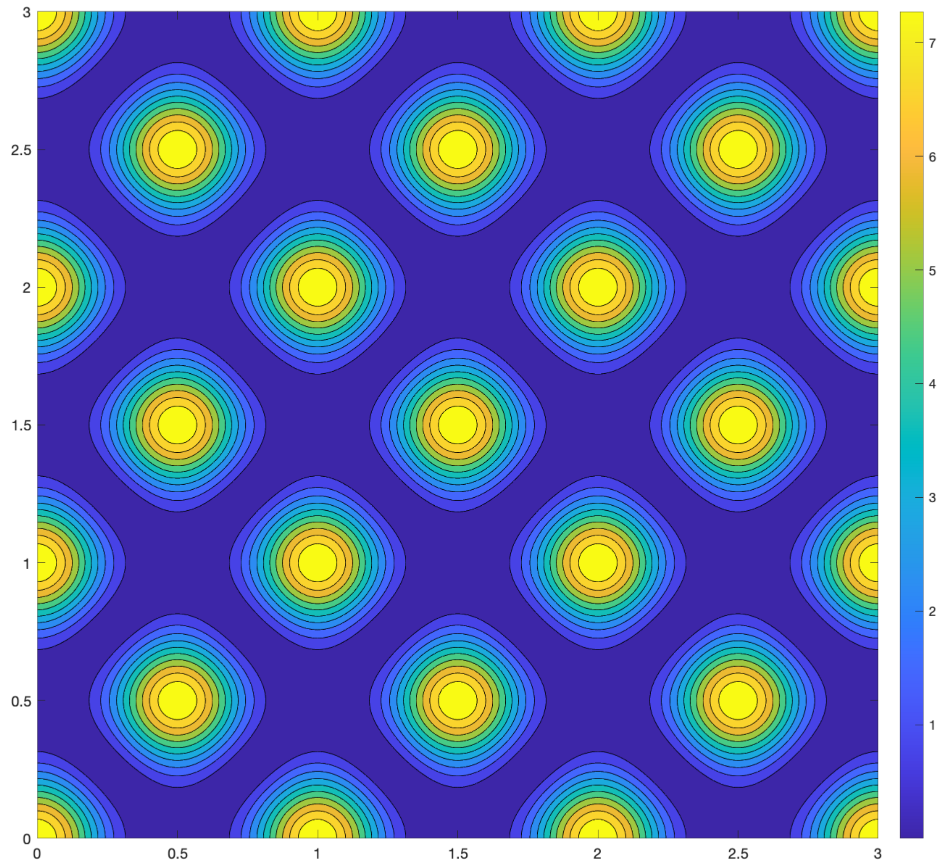



Optical lattice potential, image from <https://www.nist.gov/image/physicsquantumcomputingqubitsjpg>.

# “Manhattan” lattice



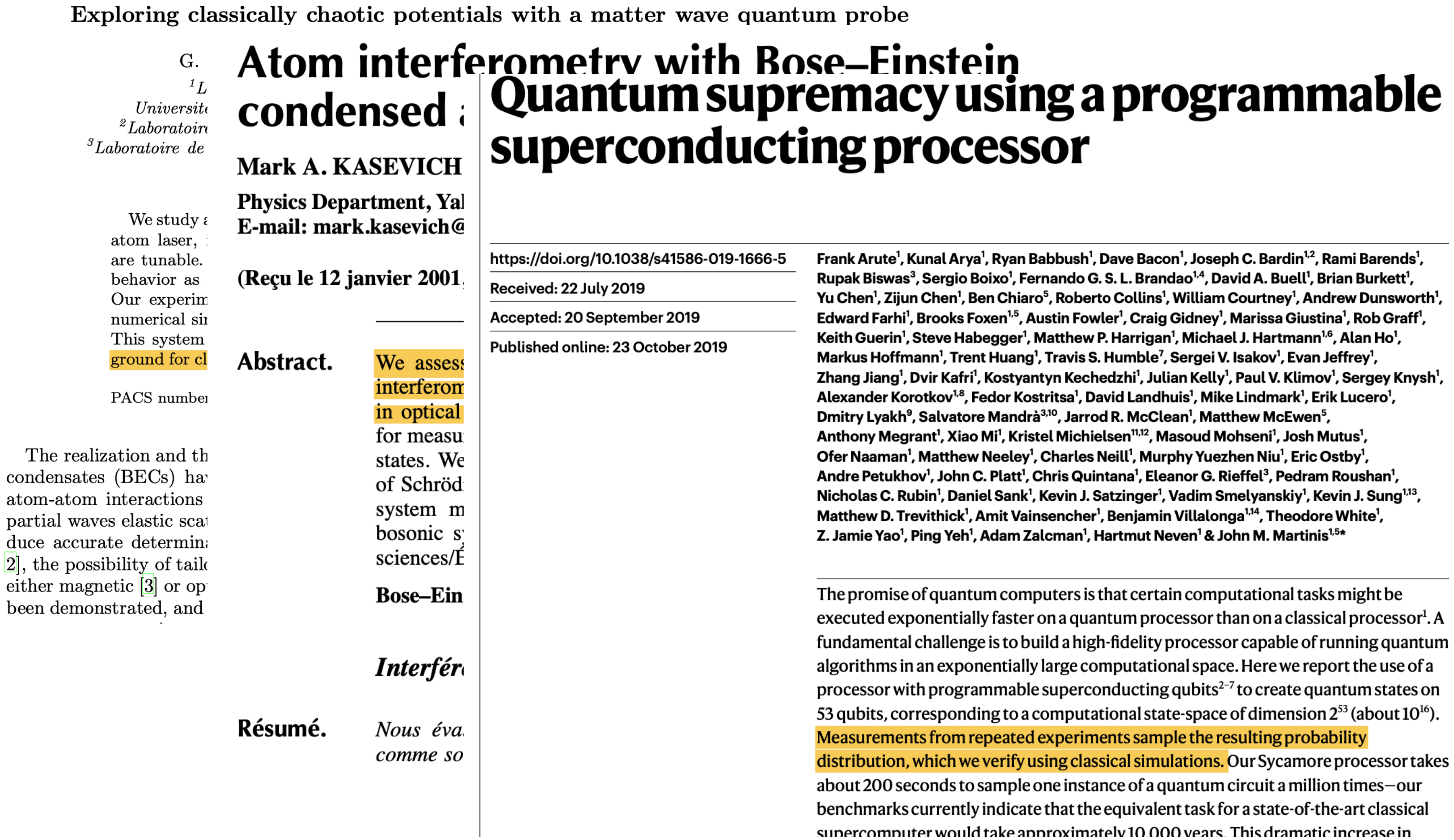

Angled view of Manhattan lattice potential.




Manhattan lattice potential, figure generated with Peter Dotti’s code.

# Motivating topics

- Quantum chaos
- Matter wave interference
- Boson sampling / quantum supremacy



Exploring classically chaotic potentials with a matter wave quantum probe

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Atom interferometry with Bose–Einstein condensed

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(Reçu le 12 janvier 2001

Abstract. We assess interferom in optical for measu states. We of Schröd system m bosonic s sciences/E

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Résumé. Nous éva comme so

# Quantum supremacy using a programmable superconducting processor

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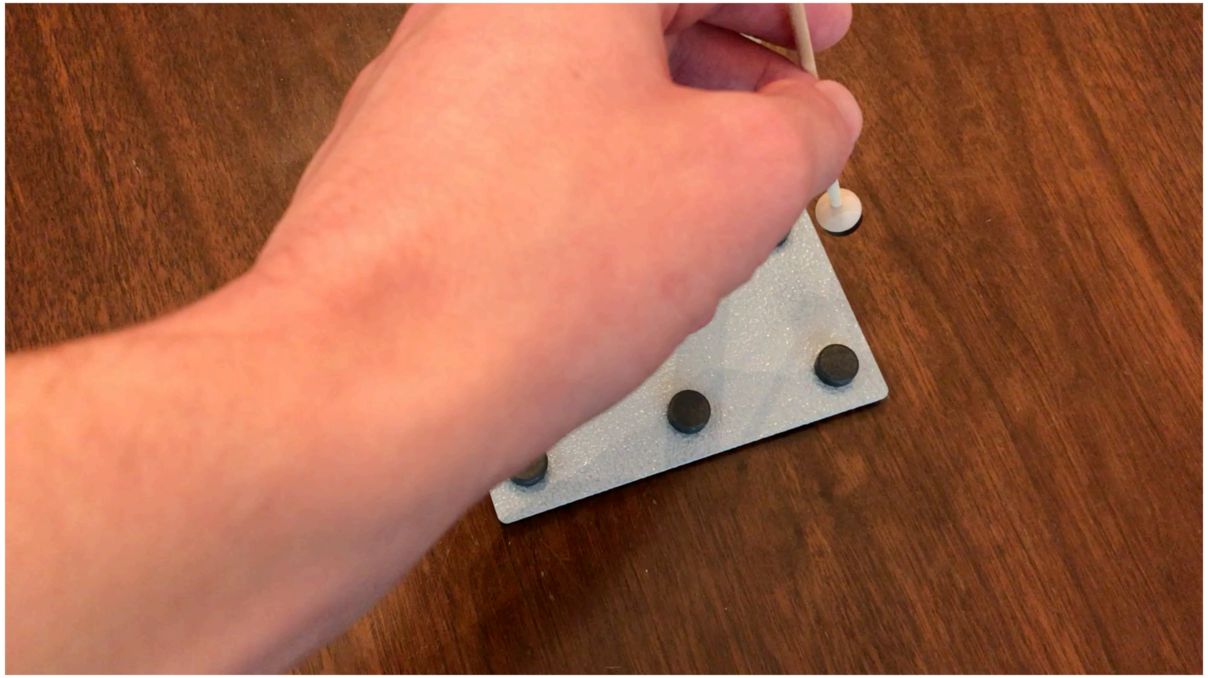
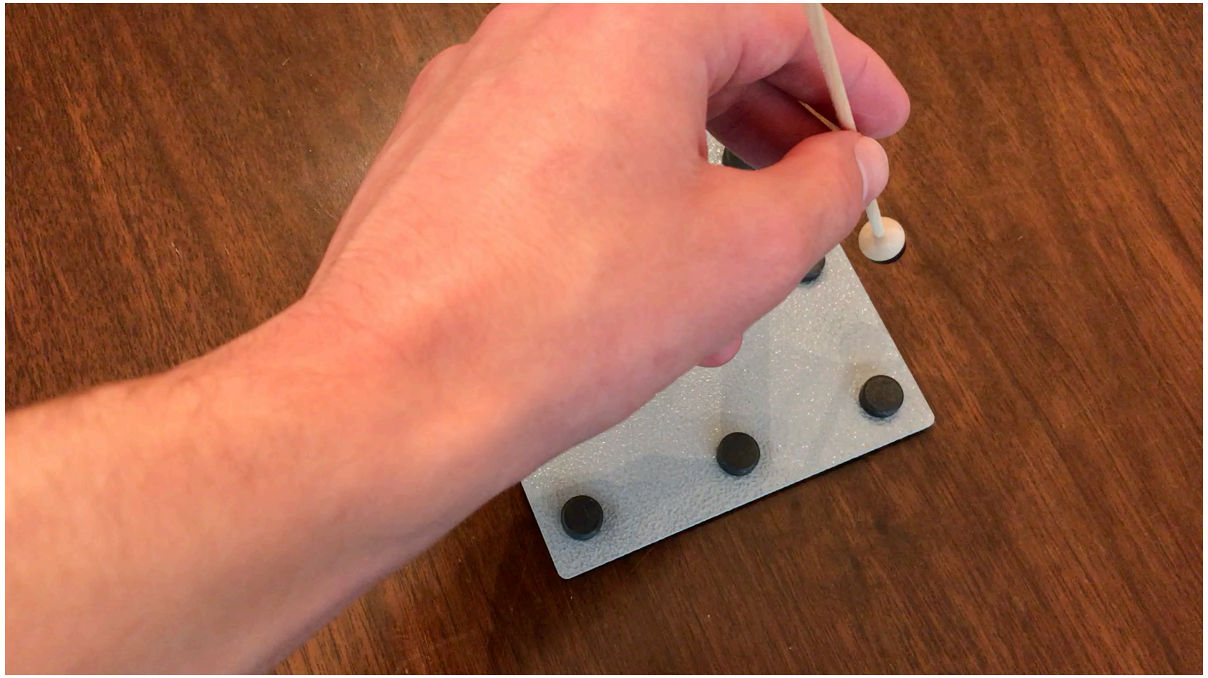
The promise of quantum computers is that certain computational tasks might be executed exponentially faster on a quantum processor than on a classical processor[1]. A fundamental challenge is to build a high-fidelity processor capable of running quantum algorithms in an exponentially large computational space. Here we report the use of a processor with programmable superconducting qubits[2–7] to create quantum states on 53 qubits, corresponding to a computational state-space of dimension $2^{53}$ (about $10^{16}$). Measurements from repeated experiments sample the resulting probability distribution, which we verify using classical simulations. Our Sycamore processor takes about 200 seconds to sample one instance of a quantum circuit a million times—our benchmarks currently indicate that the equivalent task for a state-of-the-art classical supercomputer would take approximately 10,000 years. This dramatic increase in

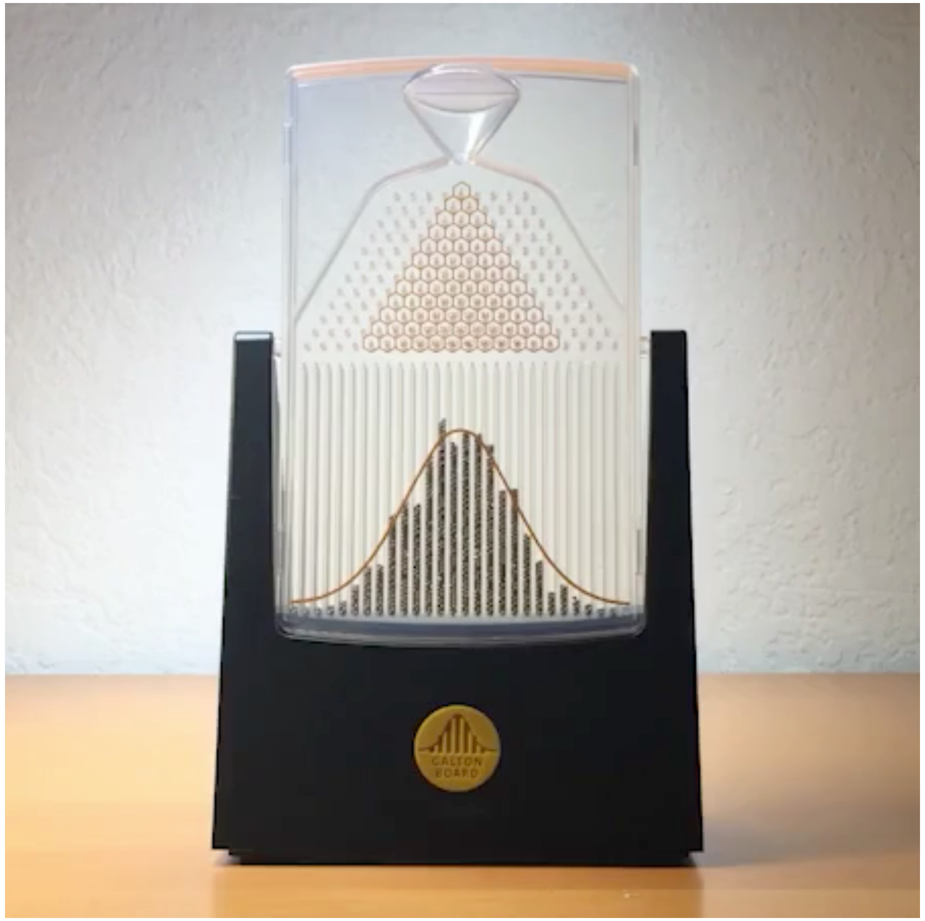
# Classical chaos

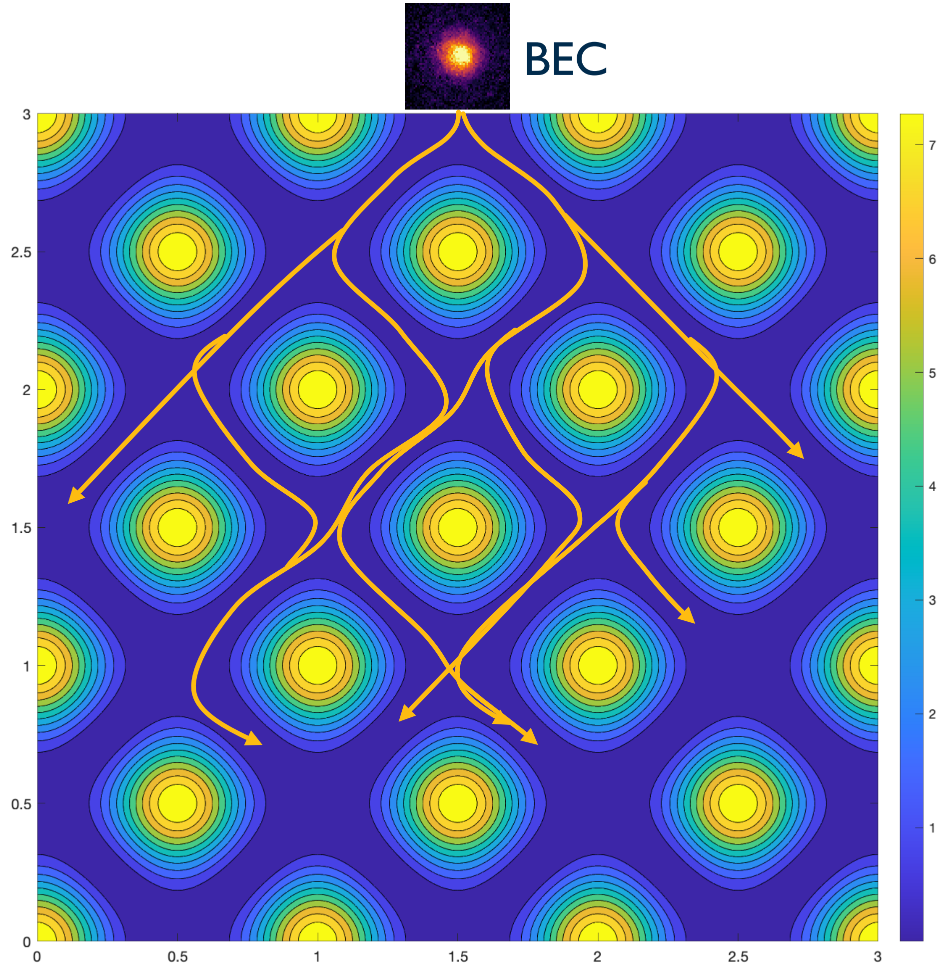




Pendulum above magnet grid, videos from Peter Dotti.

# Manhattan lattice as a Galton board

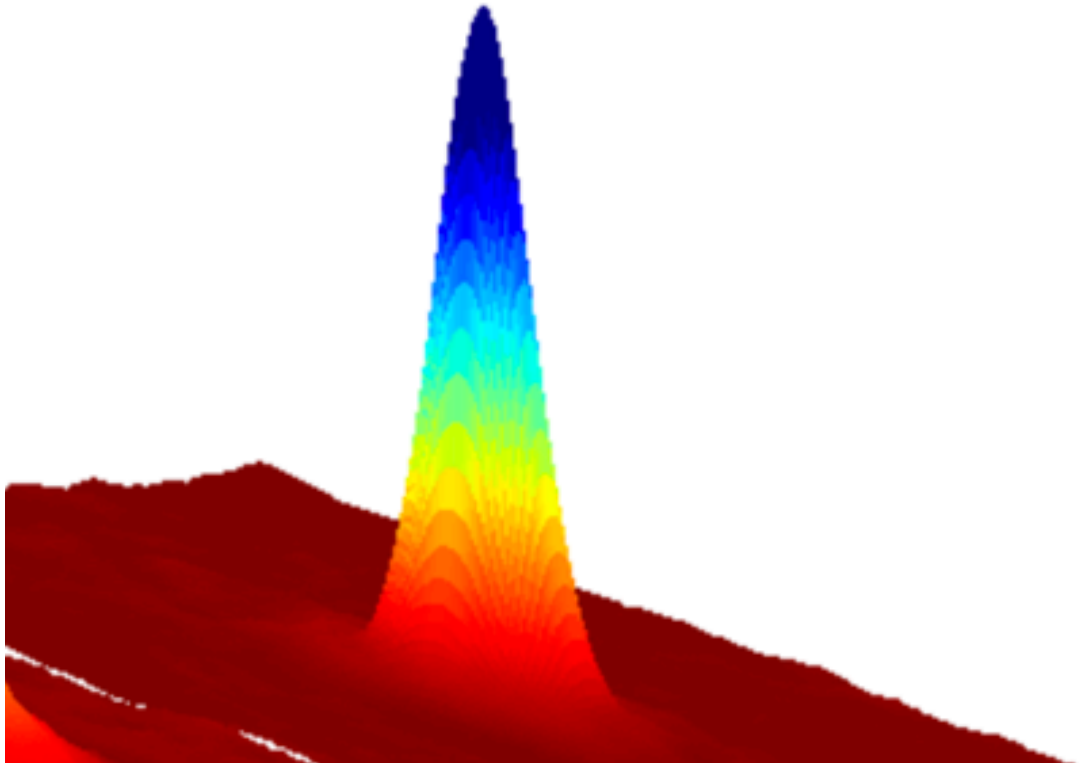




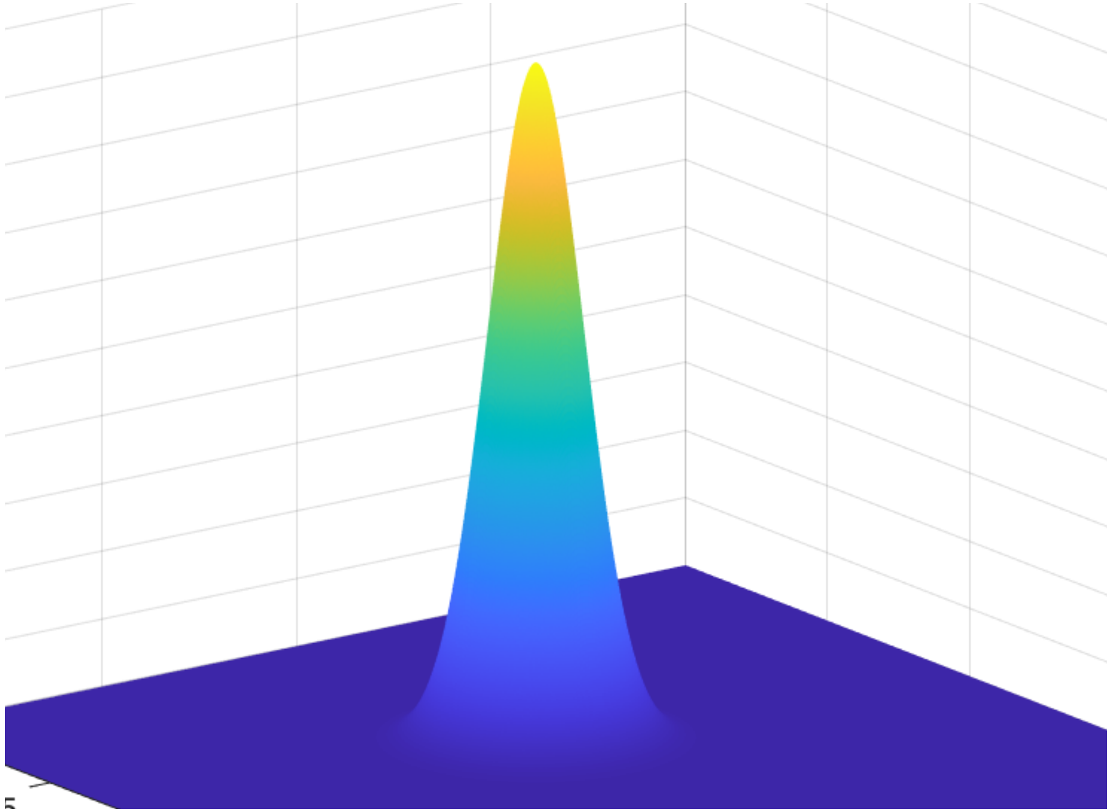

Galton board, video from <https://galtonboard.com/>.

Manhattan lattice potential, figure generated with Peter Dotti's code.

# BECs are a tool



in the lab



on the computer

# Numerical approach using MATLAB

1. Simulate BEC wave function's initial state in an optical dipole trap

2. Simulate the potential grid of the lattice

3. Time-evolve the system through ramp and free evolution

# Time evolution

$$\Psi(\mathbf{x},t) \rightarrow \boxed{e^{-i\hat{H}dt}} \rightarrow \Psi(\mathbf{x},t+dt)$$

HARD!

$$i\frac{\partial}{\partial t}\Psi(\mathbf{x},t) = \hat{H}\Psi(\mathbf{x},t) = \Big(-\nabla^2 + V(\mathbf{x},t)\Big)\Psi(\mathbf{x},t)$$

$$\frac{\partial}{\partial t}\Psi = A\Psi + B\Psi$$

$$e^{(A+B)dt} \approx e^{Adt}e^{Bdt}$$

$$A = i\nabla^2,\ B = -iV(\mathbf{x},t)$$

$$\Psi(\mathbf{x},t) \rightarrow \boxed{e^{i\nabla^2 dt}} \rightarrow \Psi'(\mathbf{x}) \rightarrow \boxed{e^{-iVdt}} \rightarrow \Psi(\mathbf{x},t+dt)$$

EASIER

$$\Psi(\mathbf{x},t) \rightarrow \boxed{\mathcal{F}} \rightarrow \Phi(\mathbf{k},t) \rightarrow \boxed{e^{-i\mathbf{k}^2 dt}} \rightarrow \Phi'(\mathbf{k}) \rightarrow \boxed{\mathcal{F}^{-1}} \rightarrow \Psi'(\mathbf{x}) \rightarrow \boxed{e^{-iVdt}} \rightarrow \Psi(\mathbf{x},t+dt)$$

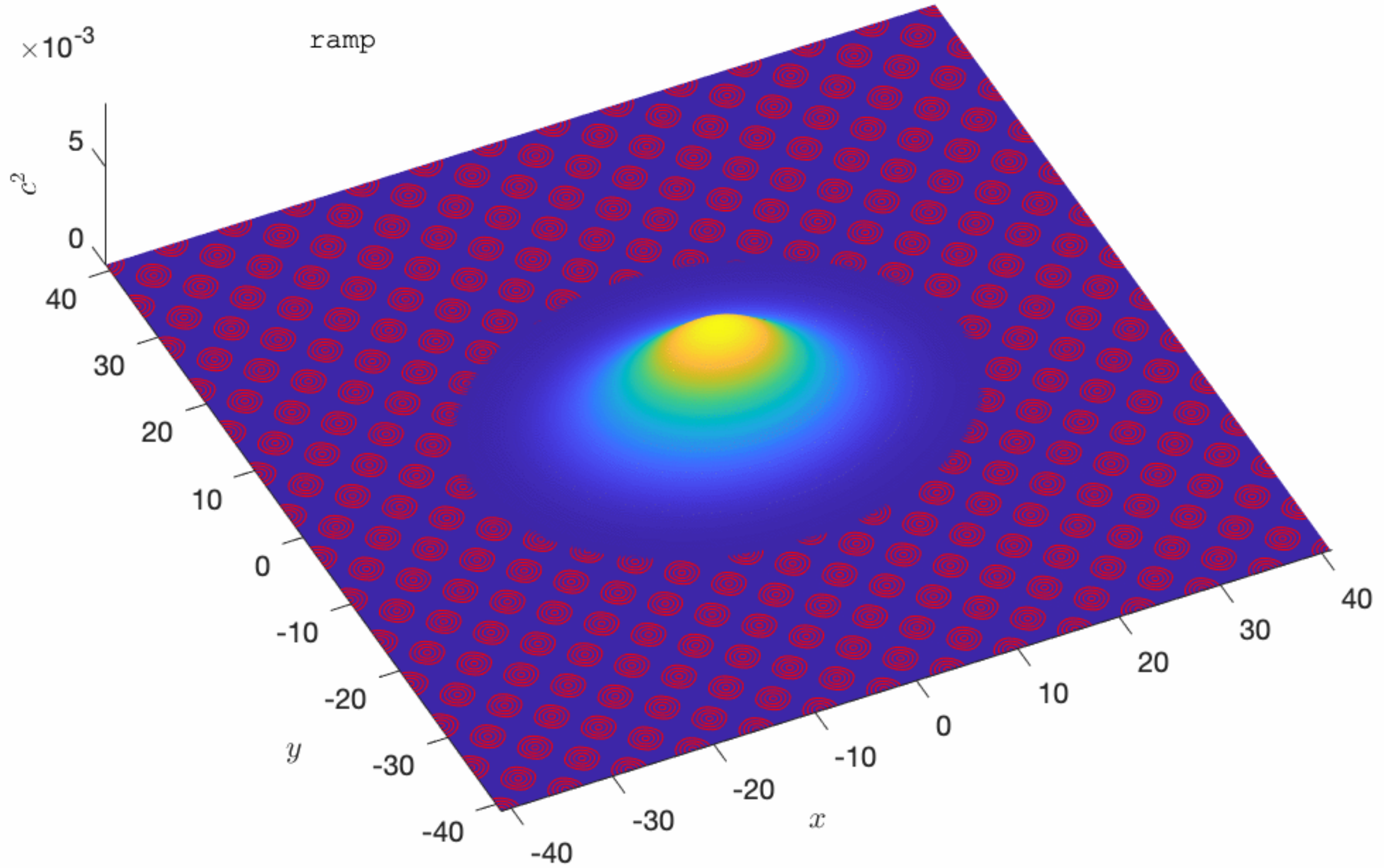
EASIEST

$$e^{(A+B)dt} \approx e^{\frac{Bdt}{2}}e^{Adt}e^{\frac{Bdt}{2}}$$

ACTUAL

$$\Psi(\mathbf{x},t) \rightarrow \boxed{e^{\frac{-iVdt}{2}}} \rightarrow \Psi'(\mathbf{x}) \rightarrow \boxed{\mathcal{F}} \rightarrow \Phi(\mathbf{k}) \rightarrow \boxed{e^{-i\mathbf{k}^2 dt}} \rightarrow \Phi'(\mathbf{k}) \rightarrow \boxed{\mathcal{F}^{-1}} \rightarrow \Psi''(\mathbf{x}) \rightarrow \boxed{e^{\frac{-iVdt}{2}}} \rightarrow \Psi(\mathbf{x},t+dt)$$

# Evolving a Gaussian



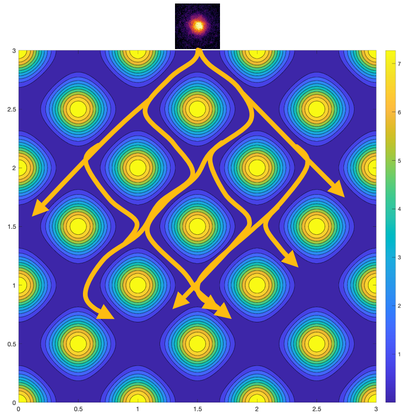
# Next step: interactions!

Schrödinger equation: $$i\hbar\frac{\partial}{\partial t}\Psi = \hat{H}\Psi = \left(-\nabla^2 + V(\mathbf{x})\right)\Psi$$

Gross-Pitaevskii equation: $$i\hbar\frac{\partial\Psi}{\partial t} = \left(-\frac{\hbar^2}{2m}\nabla^2 + V(\mathbf{x}) + \boxed{g|\Psi|^2}\right)\Psi$$

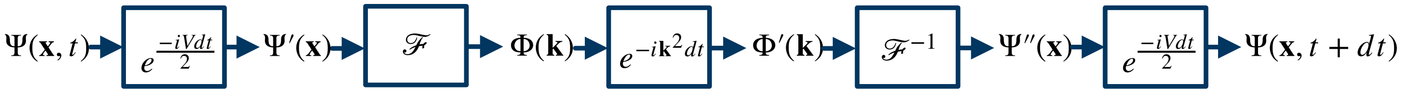
interaction term

# Summary

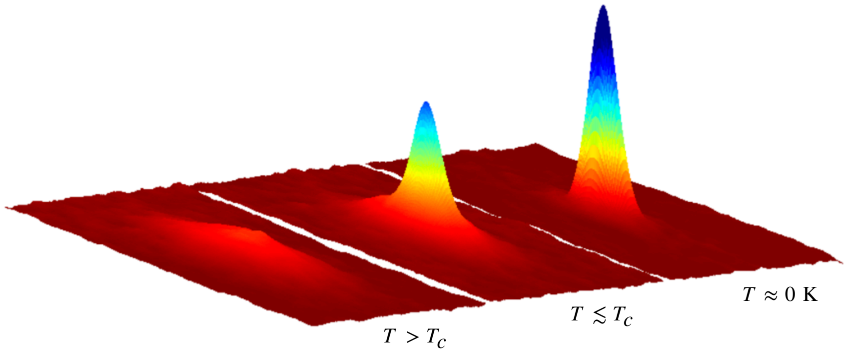


Question: quantum dynamics in Manhattan lattice

Numerical approach: time-splitting




Experimental approach: Bose-Einstein condensates



# Acknowledgements

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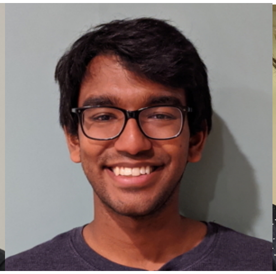

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Jeremy Tanlimco

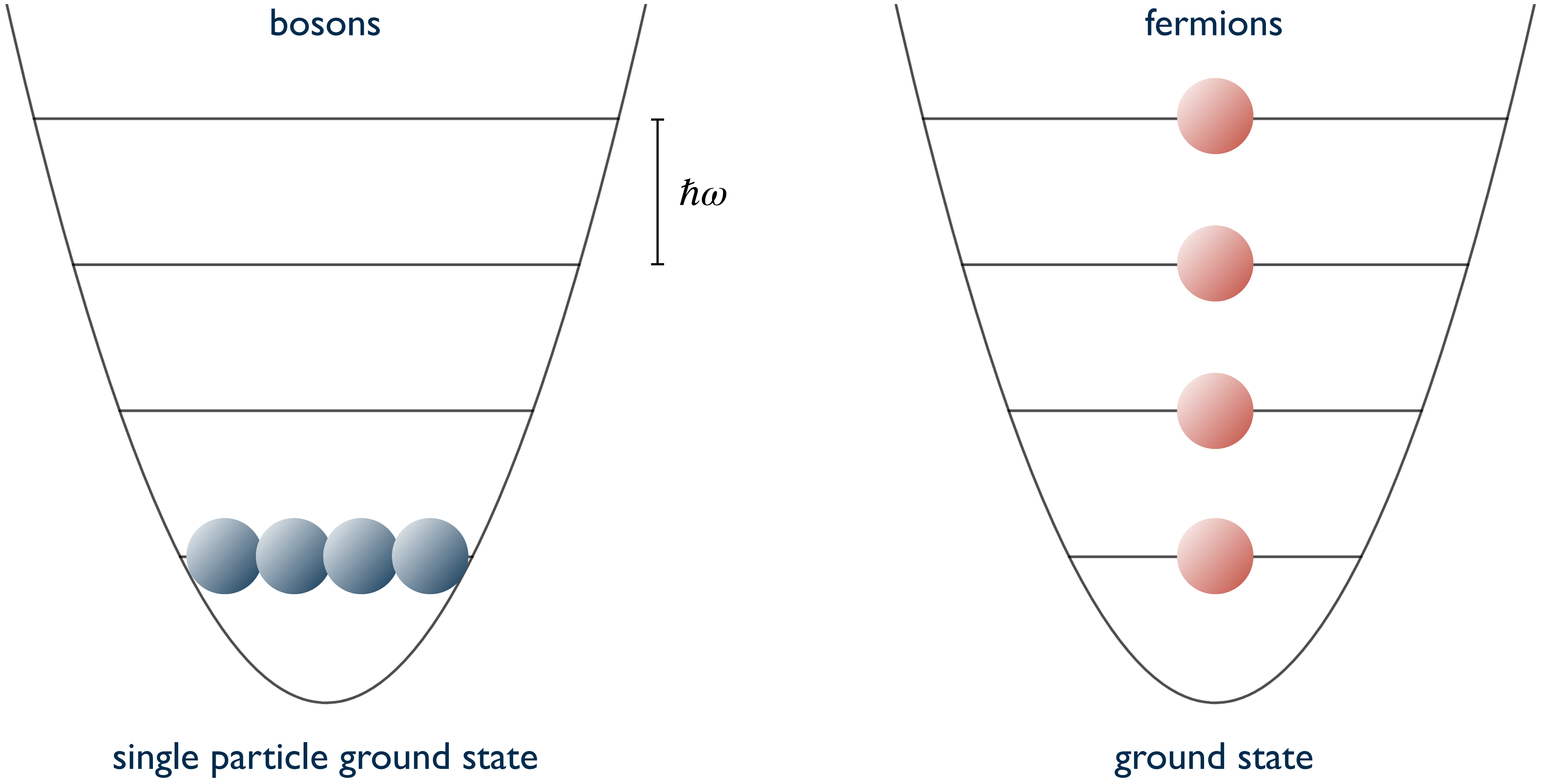
Alec Cao

Max Prichard

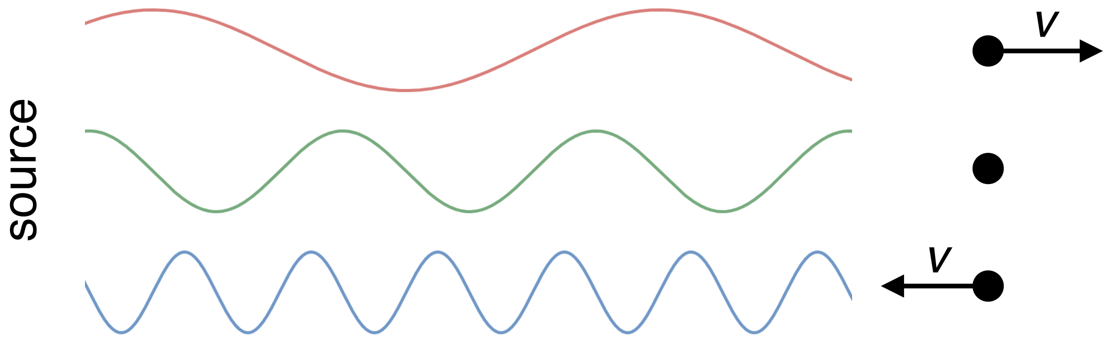
Katya Weiss

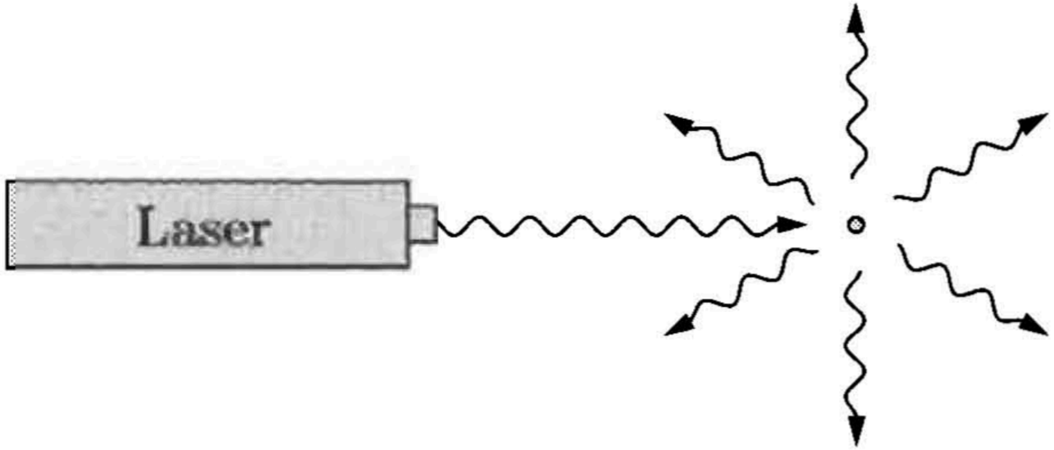
Jack Pan

# Bosons vs. Fermions



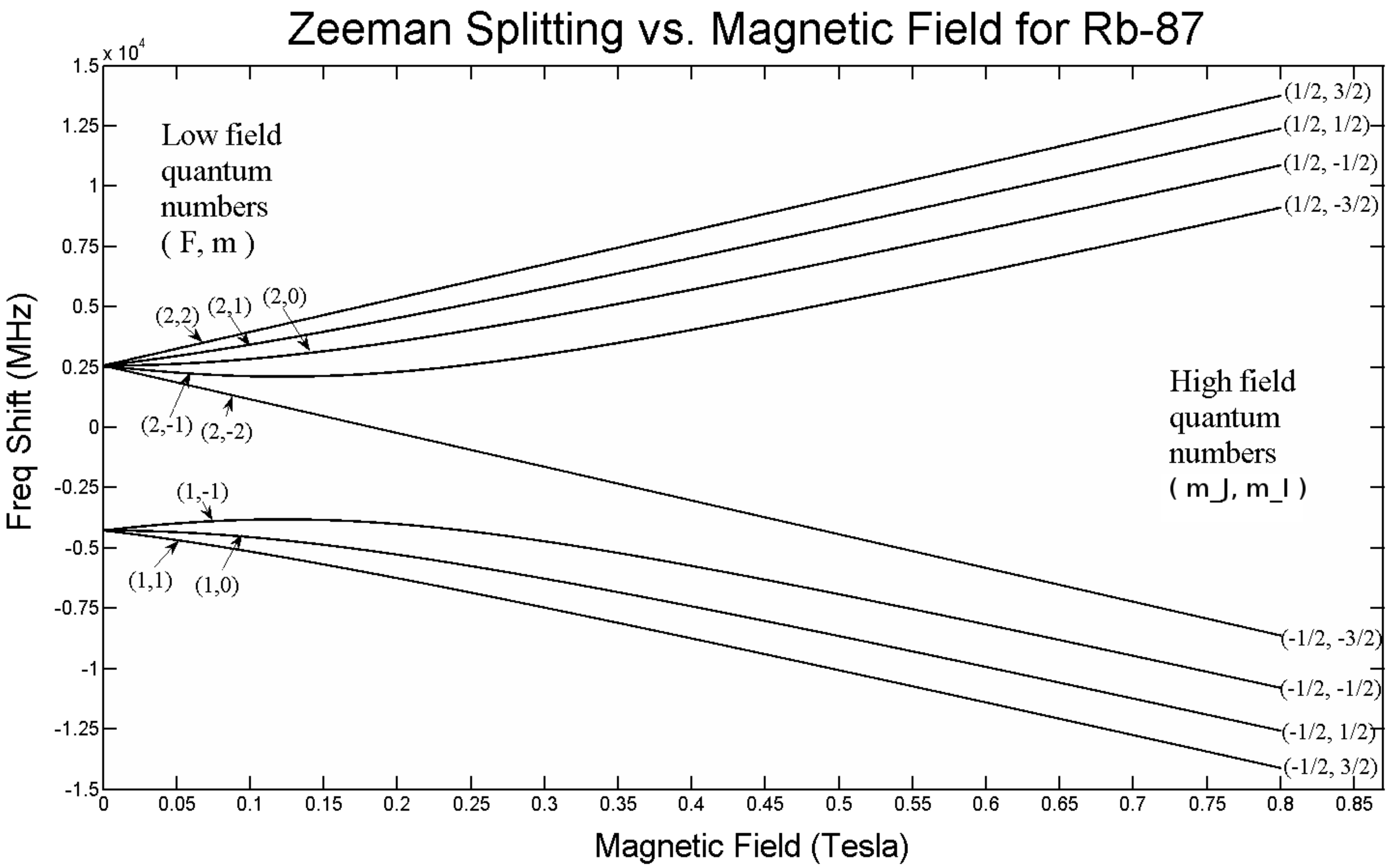
# Laser cooling



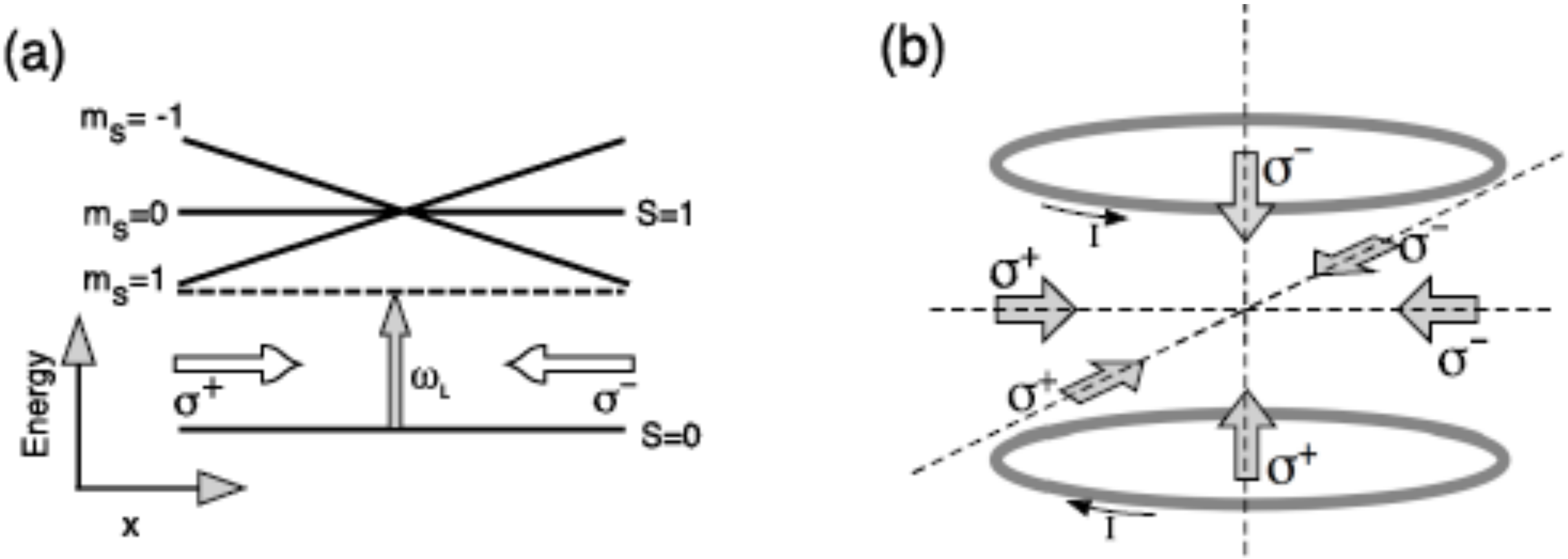

Laser cooling, figure from Schroeder, *An Introduction to Thermal Physics*.

# The Zeeman effect



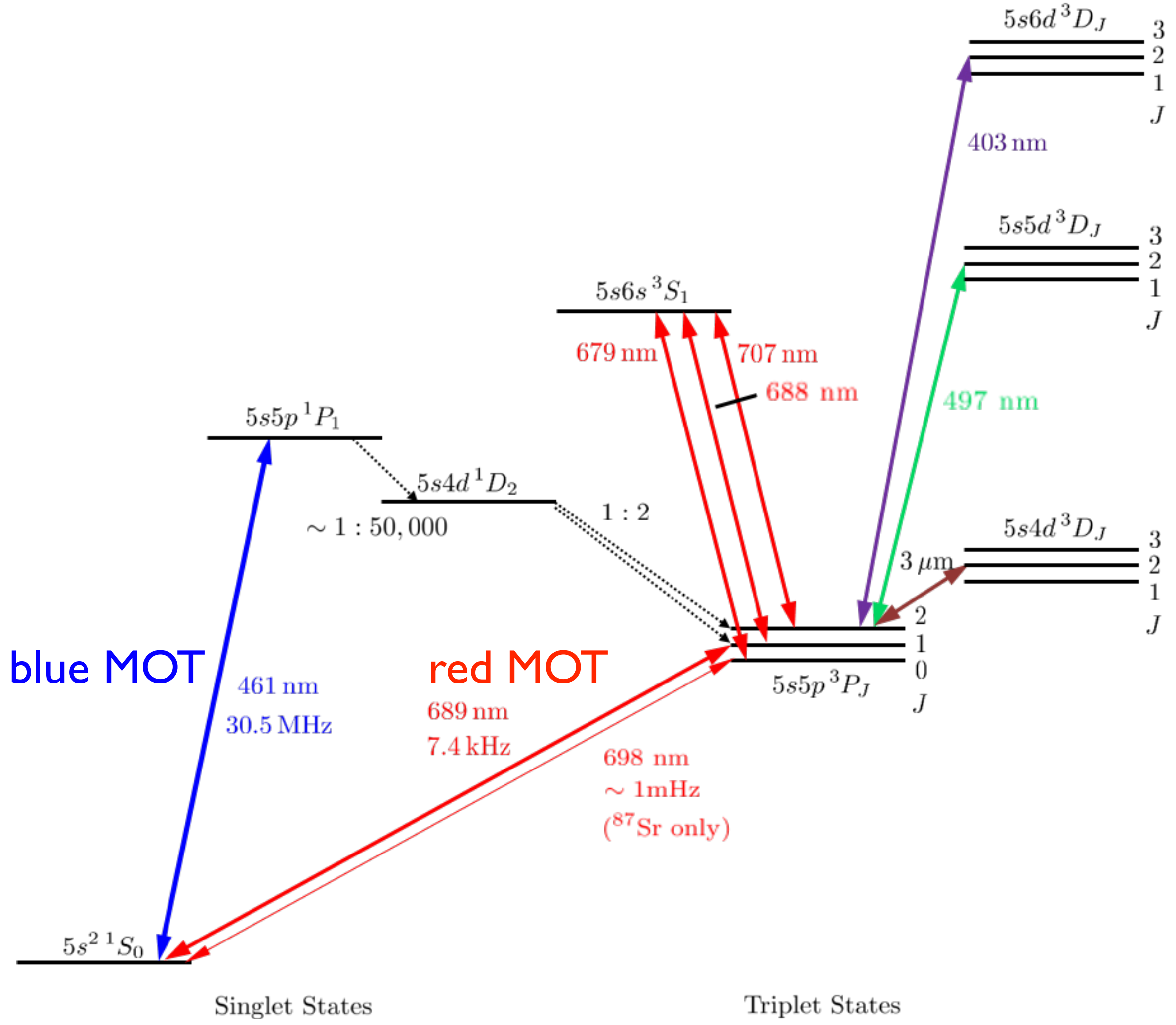

https://upload.wikimedia.org/wikipedia/commons/5/56/Breit-rabi-Zeeman.png.

# Magneto-optical traps




Robinson, J0hn M, Liu, Yu, Shelton, David P. “Development and Characterization of a Magneto-Optical Trap for Rubidium.” Nevada State Undergraduate Research Journal. V1:I1 Fall-2014. (2014). http://dx.doi.org/10.15629/6.7.8.7.5_1-1_F-2014_2.

# Level structure of strontium-84




Strontium-84 level structure diagram, figure from Stellmer thesis.