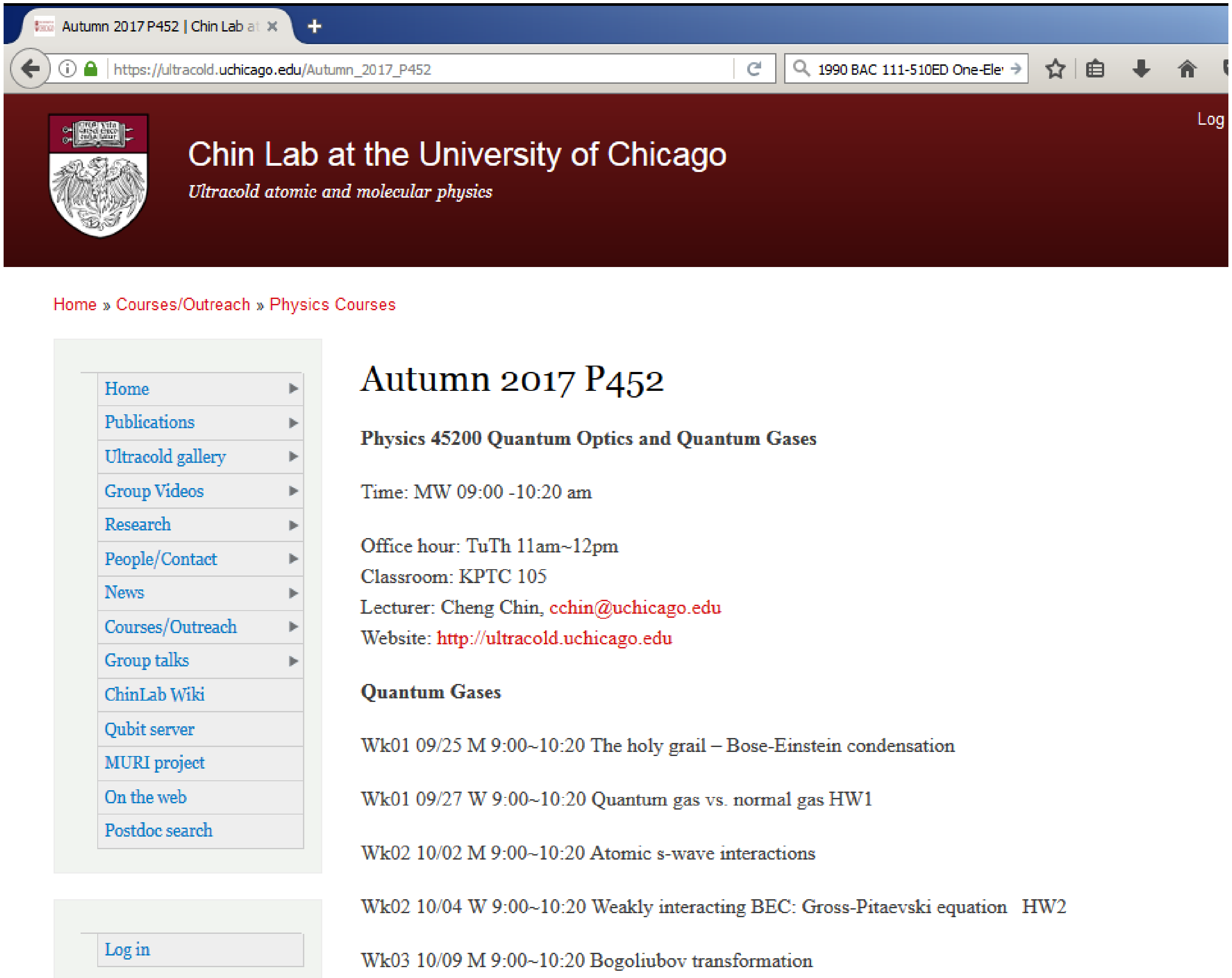
# *Physics 452 – Quantum Optics and Quantum Gases*

*Class information: https://ultracold.uchicago.edu/phys_courses*



Autumn 2017 P452 | Chin Lab at

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Chin Lab at the University of Chicago

*Ultracold atomic and molecular physics*

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## Autumn 2017 P452

**Physics 45200 Quantum Optics and Quantum Gases**

Time: MW 09:00 -10:20 am

Office hour: TuTh 11am~12pm
Classroom: KPTC 105
Lecturer: Cheng Chin, cchin@uchicago.edu
Website: http://ultracold.uchicago.edu

**Quantum Gases**

Wk01 09/25 M 9:00~10:20 The holy grail – Bose-Einstein condensation

Wk01 09/27 W 9:00~10:20 Quantum gas vs. normal gas HW1

Wk02 10/02 M 9:00~10:20 Atomic s-wave interactions

Wk02 10/04 W 9:00~10:20 Weakly interacting BEC: Gross-Pitaevski equation HW2

Wk03 10/09 M 9:00~10:20 Bogoliubov transformation

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Wk03 10/09 M 9:00~10:20 Weakly interacting BEC: Bogoliubov transformation
Wk03 10/11 W 9:00~10:20 Cold collisions and Feshbach resonances HW3
Wk04 10/16 M 9:00~10:20 Strongly interacting gas: Bosons vs. Fermions
Wk04 10/18 W 9:00~10:20 ***Lab Tour***
Wk04 10/23 M 9:00~10:20 Ultracold molecules
Wk05 10/25 W 9:00~10:20 Optical lattices HW4
Wk06 10/30 M 9:00~10:20 Presentations 1 + Midterm

*Physics 452 – Quantum Optics and Quantum Gases*

**Quantum Optics**
Wk06 11/01 W 9:00~10:20 Inelastic and elastic (Rayleigh) scattering HW5
Wk07 11/06 M 9:00~10:20 Light shifts and dressed atom picture
Wk07 11/08 W 9:00~10:20 Precision measurements HW6
Wk07 11/10 F 9:00~10:20 Coherent states and squeezed states
Wk08 11/13 M 9:00~10:20 Photon entanglement HW7
Wk08 11/15 W 9:00~10:20 ***No Class***
Wk08 11/20 M 9:00~10:20 Quantum teleportation
Wk09 11/22 M 9:00~10:20 Cavity QED
Wk09 11/27 M 9:00~10:20 Quantum computation HW8
Wk09 11/29 W 9:00~10:20 Presentations 2 + Final

**Evaluation**
Problem sets 40%
Midterm 20%
Final 20%
Final paper/presentation 30%

# Presentations

Quantum gas

- Radio Frequency Magneto-Optical Trapping of CaF with High Density: *Phys. Rev. Lett.* **119**, 103201 (2017)
- Formation of matter-wave soliton trains by modulation instability: Science ***356***, 422 (2017)
- Creation of a Bose-condensed gas by laser cooling: arXive: 1705.03421
- An atom-by-atom assembler of defect-free arbitrary 2d atomic arrays: *Science*, **354**, 1021 (2016)

Quantum optics

- Quantum superpositions at metre scales: Nature ***528***, 530-533 (2015), Nature ***537***, E1-E2 (2015), and arXive:1607.03485.
- Loophole-free Bell inequality violation using electron spins separated by 1.3 km: Nature ***526***, 682 (2015)
- Bell correlations in thermal gas and Bose condensates: Physical Review Letters, **118**, 140401 (2017), Science ***352***, 441 (2016)
- Entanglement of almost 3,000 atoms heralded by one photon: Nature ***519***, 7544 (2017)
- Cavity Cooling of many atoms: Physical Review Letters ***118***, 183601 (2017)

# *Physics 452 – Quantum Optics and Quantum Gases*

**Supporting texts**

*Quantum gases:*

Bose-Einstein Condensation in Dilute Gases by C. J. Pethick and H. Smith
Bose-Einstein Condensation by L. Pitaevskii, S. Stringari
G.-P. equation and Bogoliubov approximation, A.J. Leggett, *New J. Phys.* **5** 103 (2003)

*Review papers:*

The cold atom Hubbard toolbox, Annals of Physics **315** 52 (2005)
Theory of Bose-Einstein condensation in trapped gases, RMP **7**1 463 (1999)
Theory of ultracold atomic Fermi gases, RMP **80** 1215 (2008)
Many-body physics with ultracold gases, RMP **80** 885 (2008)
Feshbach resonances in ultracold gases, RMP **82** 1225 (2010)

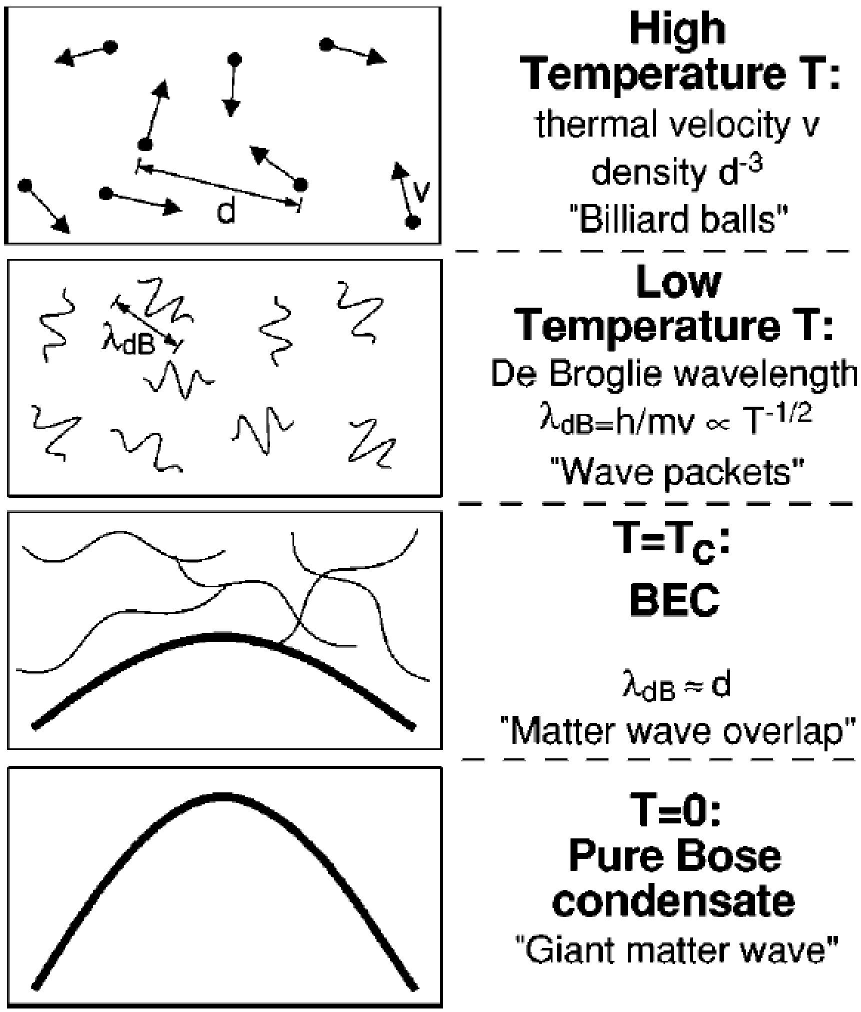
*Quantum optics:*

Quantum Optics by M. Scully and S. Zubairy
Mesoscopic Quantum Optics by Y. Yamamoto and A. Imamoglu
Quantum Optics by D. F. Walls and G. J. Milburn
Electromagnetic Noise and Quantum Optical Measurements by Hermann A. Haus

*Review papers:*

Modern approach to quantum optics: S.L. Braunstein and P. van Loock, *RMP* **77** 513 (2005)
Photon echos: I.D. Abella, N.A. Kurnit, and S.R. Hartmann, *Phys. Rev.* **141** 391 (1966)
Continuous-variable optical quantum-state tomography: RMP 81 **299** (2009)
Linear optical quantum computing with photonic qubits: RMP 79 135 (2007)

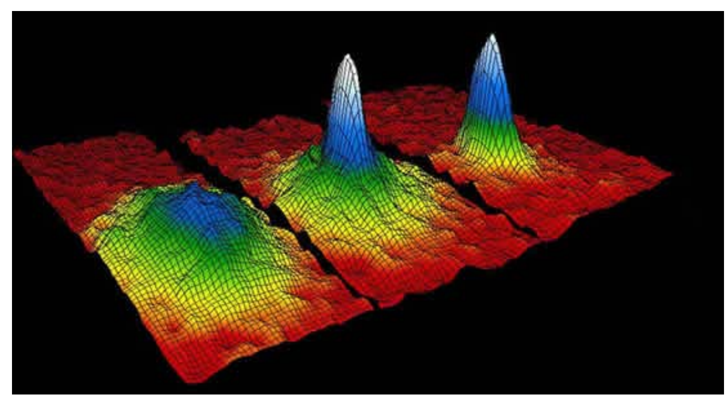
# Phase space density



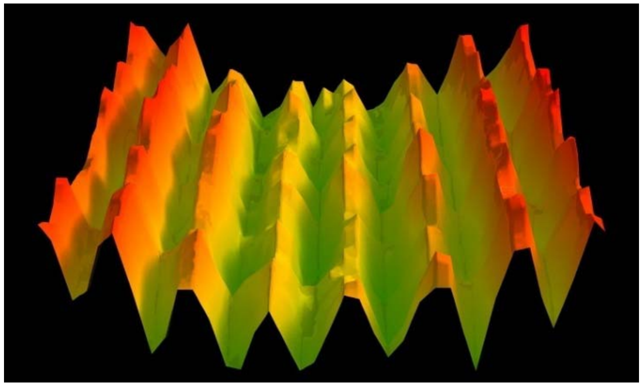

Classical mechanics:
# of particle in a unit phase space

$$\phi = NP(E_0)$$
$$= n\lambda_{dB}{}^3$$
$$\sim Ne^{-H(x,p)/kT}(dxdp/\hbar)^3$$

Quantum Mechanics:
# of particle in the ground state

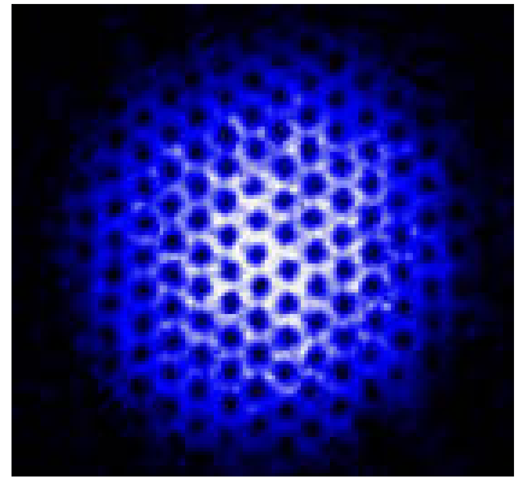


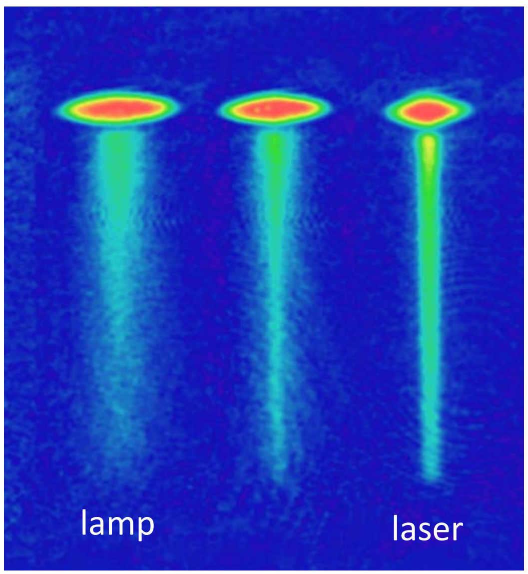
# BEC as a coherent source of matterwave (1995~2001)



Matter waves Interference
(MIT group, 1997)

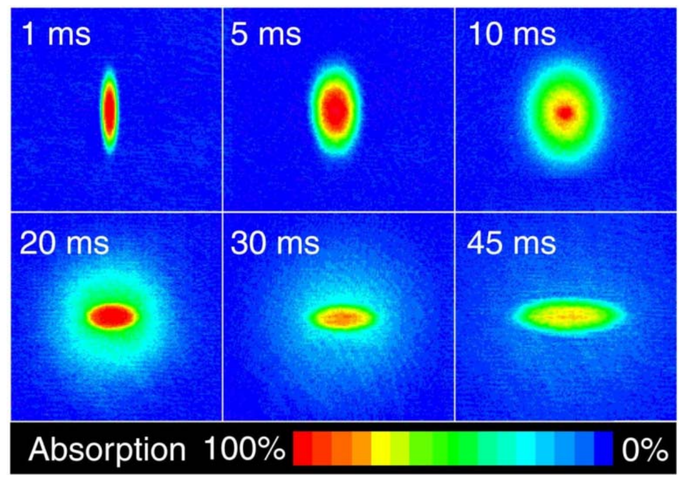
Vortices in Bose-Einstein Condensation
(JILA group, 2000)





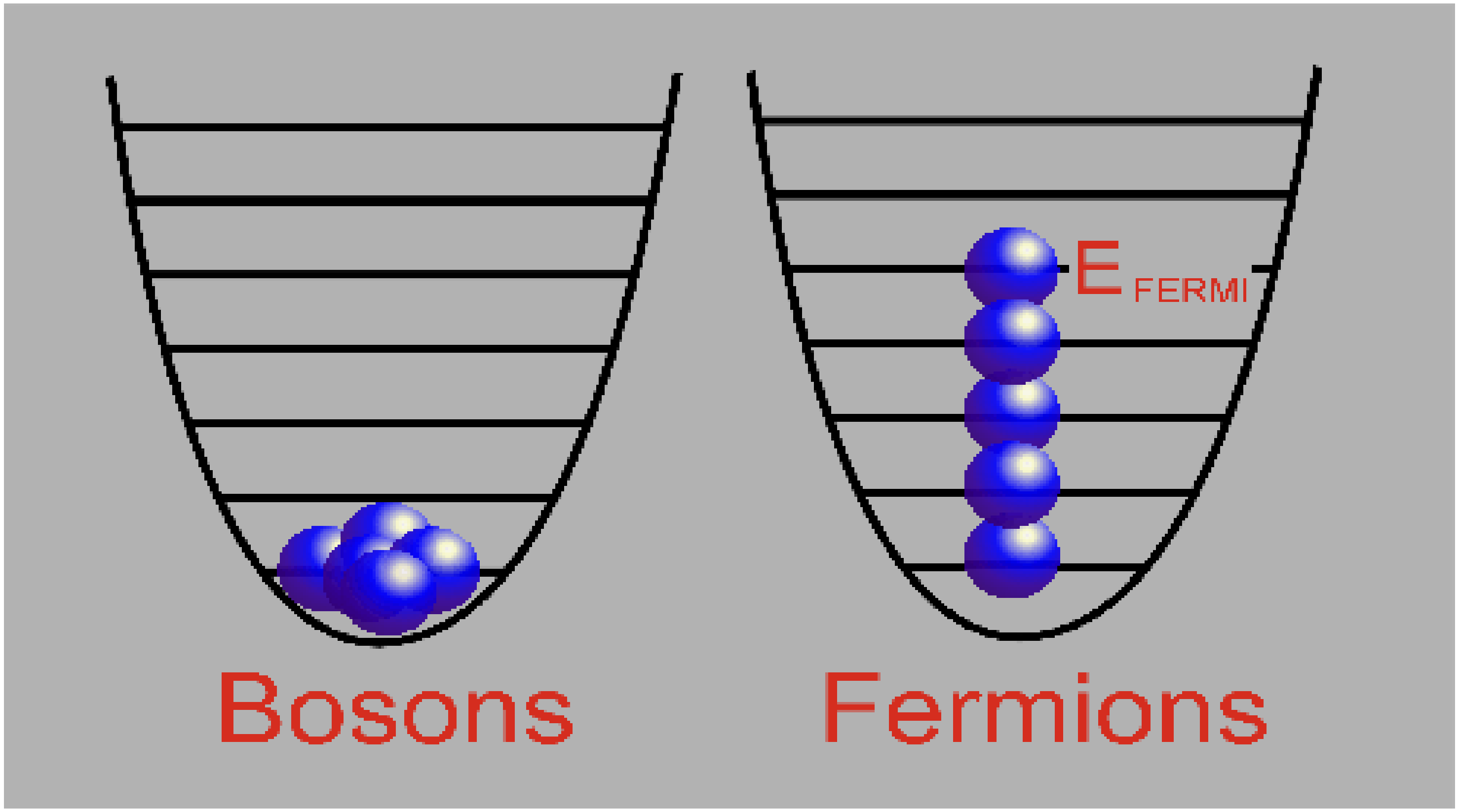

Matter wave laser
(MPQ group, 2000)

Anisotropic expansion
(JILA, MIT, 1996)

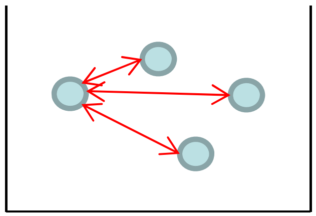



Which experiment really prove Bose-Einstein condensation?

Non-interacting BEC and Fermi gas



# Interacting gas



Many-body approach

$$H(x_1, x_2 ... x_N, p_1, p_2 ... p_N)\psi(x_1, x_2 ... x_N) = E\psi(x_1, x_2 ... x_N)$$

$$H = \sum_i \frac{\hat{p}_i^2}{2m} + \hat{V}(x_i) + \sum_{i<j} V(|x_i - x_j|)$$

Mean field approach: introduce one more particle in the system

$$H(x, p)\phi(x) = \mu\phi(x) \qquad \mu = \frac{\partial E}{\partial N} \qquad g : \text{coupling constant}$$

$$H = \frac{p^2}{2m} + \hat{V}(x) + g\frac{N}{V} \qquad \psi(x) = \sqrt{N}\phi(x)$$

Gross-Pitaevskii Equation: $(\frac{p^2}{2m} + \hat{V}(x) + g|\psi|^2)\psi = \mu\psi$