Welcome to 8.421 Atomic and Optical Physics I

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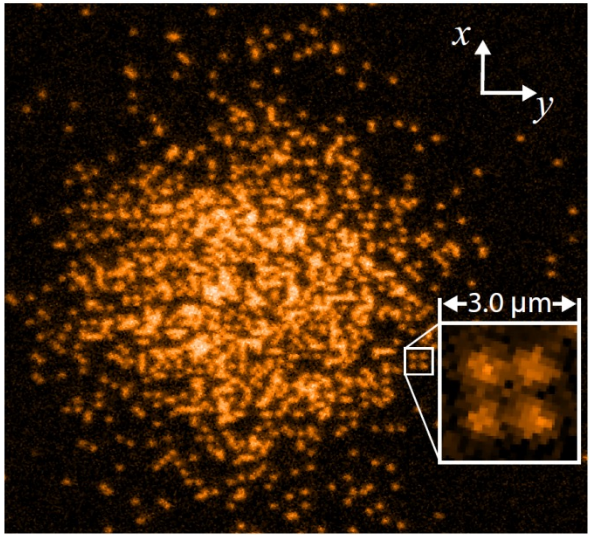


Course Requirements:

Homework (50% of grade): Assignments are due on Friday at 5pm outside my office 26-255
Midterm (20% of grade): Tentatively: Thursday, March 17th in class (11:00-12:30).
(closed book ---- all necessary formulae will be provided. Exam will test understanding, rather than memorization).
Term paper (30% of grade): Due on Tuesday May 10th (MIT last day of classes)
Please submit online via Canvas.

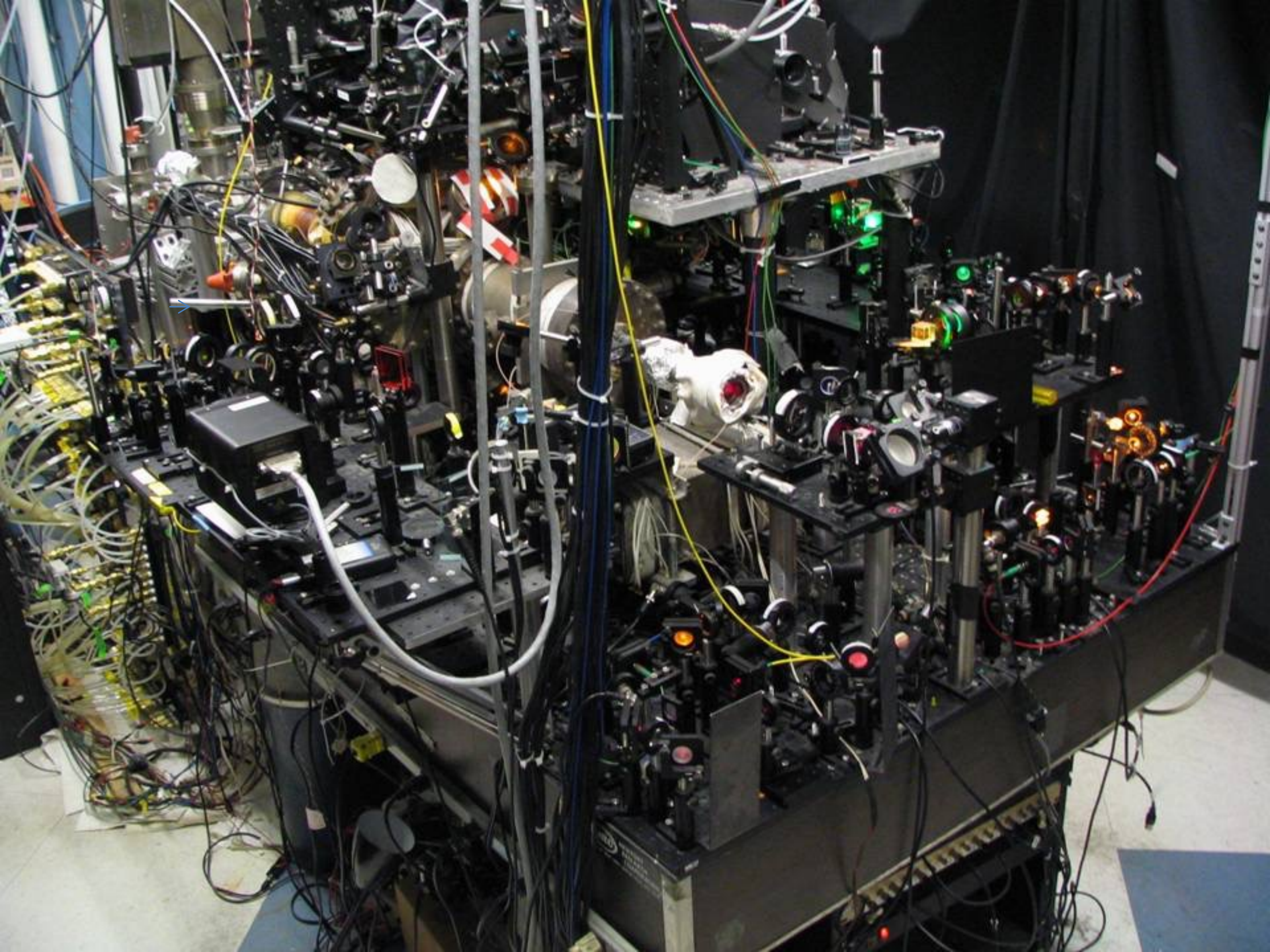
Website: https://canvas.mit.edu/courses/13870

Lecture notes: Notes will be available typically within one day after class;

Class preparation: In some cases, I will post material to be read before class

8.421 Atomic Physics I

A Brief History of Atomic Physics



How cold is ultracold?

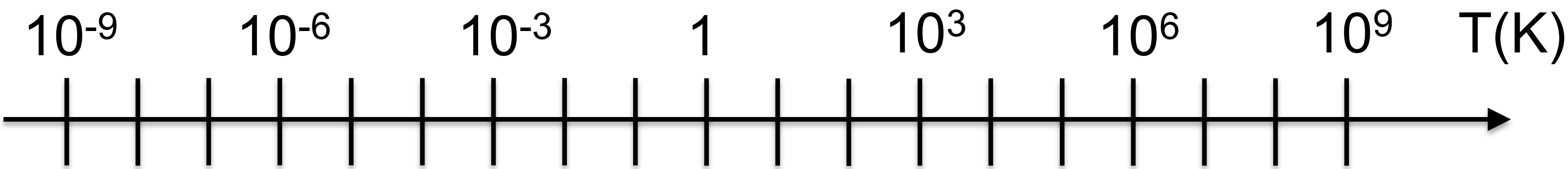
Atoms move at:

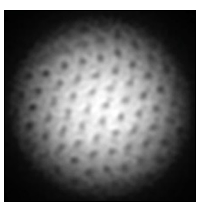
~ 1 mm/s

~ 100 m/s

~ 10^6 m/s

Boston – Paris in 10 seconds

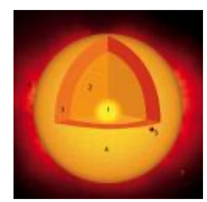




Ultracold **atom experiments**

Outer space

Your living room



Center of the sun

Supernova explosion

Particles behave as waves

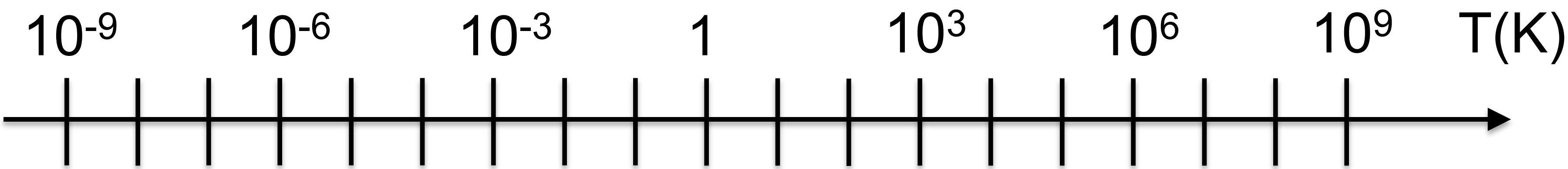
Louis de Broglie

$$\lambda = \frac{h}{mv}$$

Planck's constant

Mass

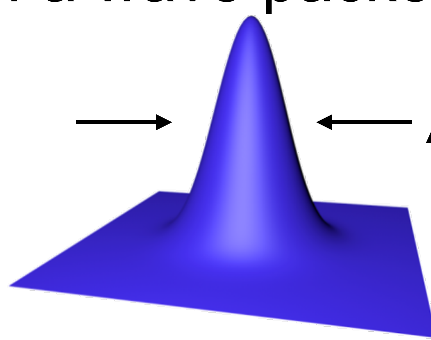
Velocity



Werner Heisenberg

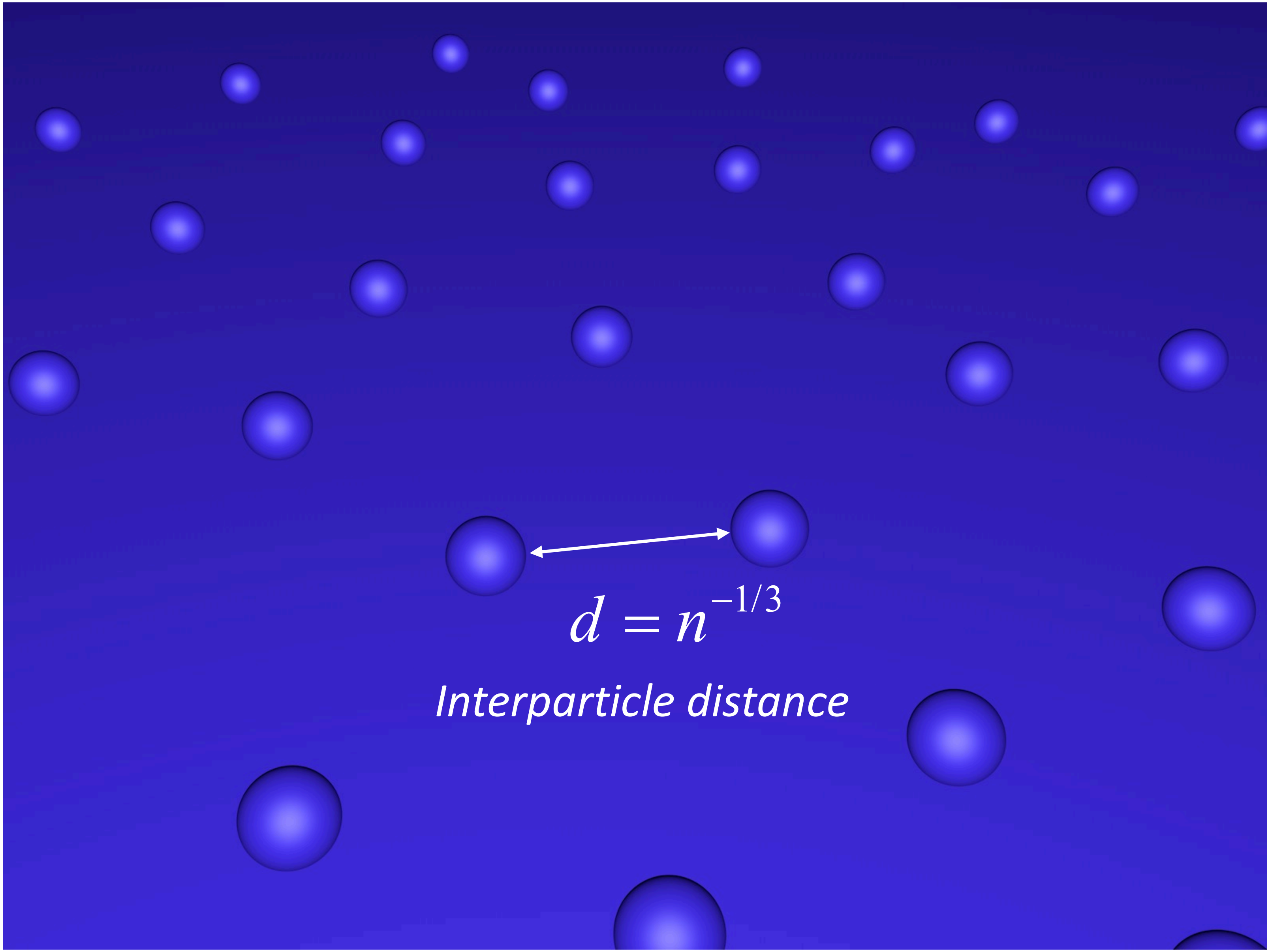
Temperature = Uncertainty of velocity^2

Size of a wave packet = Uncertainty of position

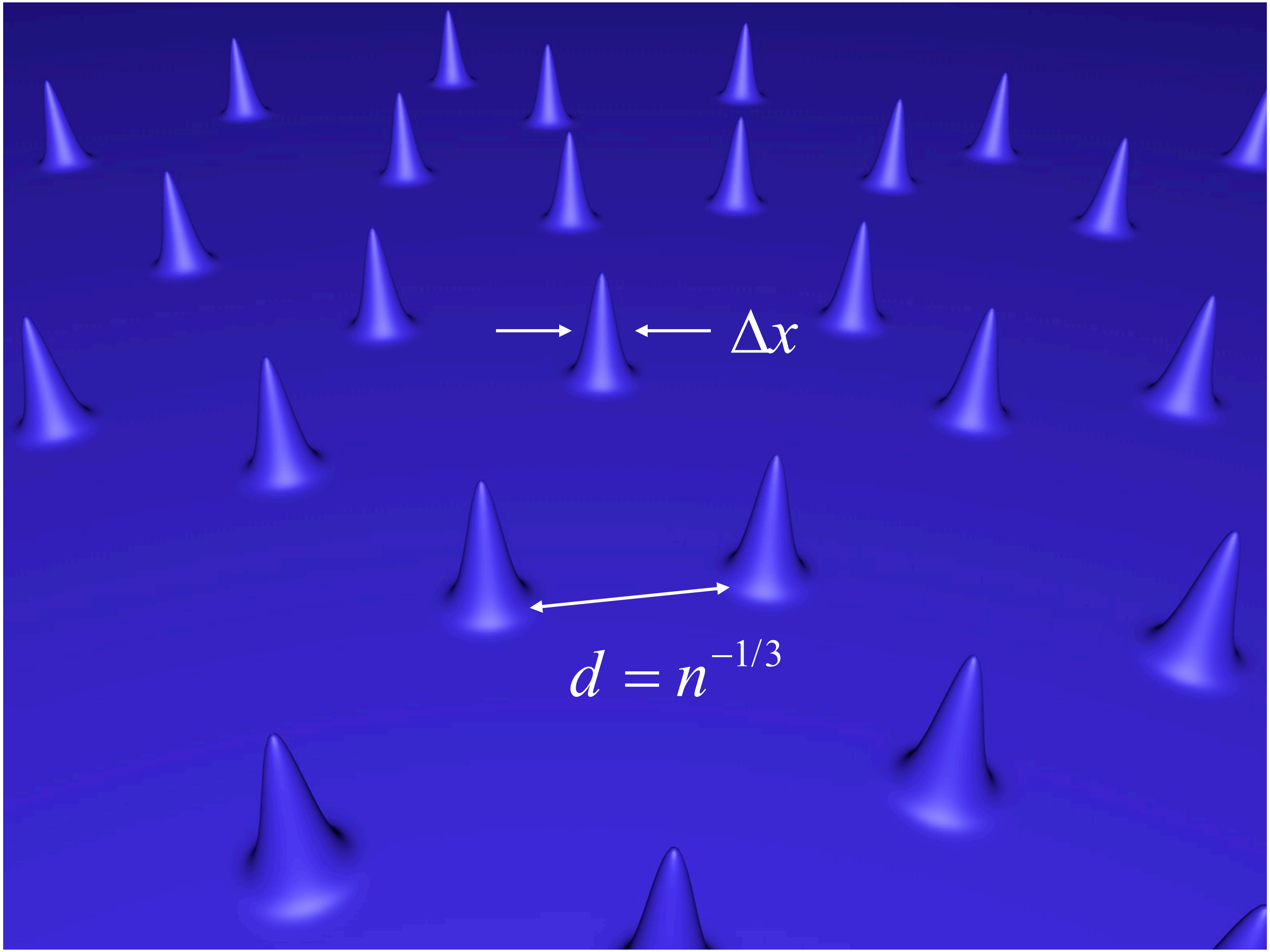


$$\Delta x \approx \frac{\hbar}{\Delta p} \approx \frac{\hbar}{\sqrt{mT}}$$

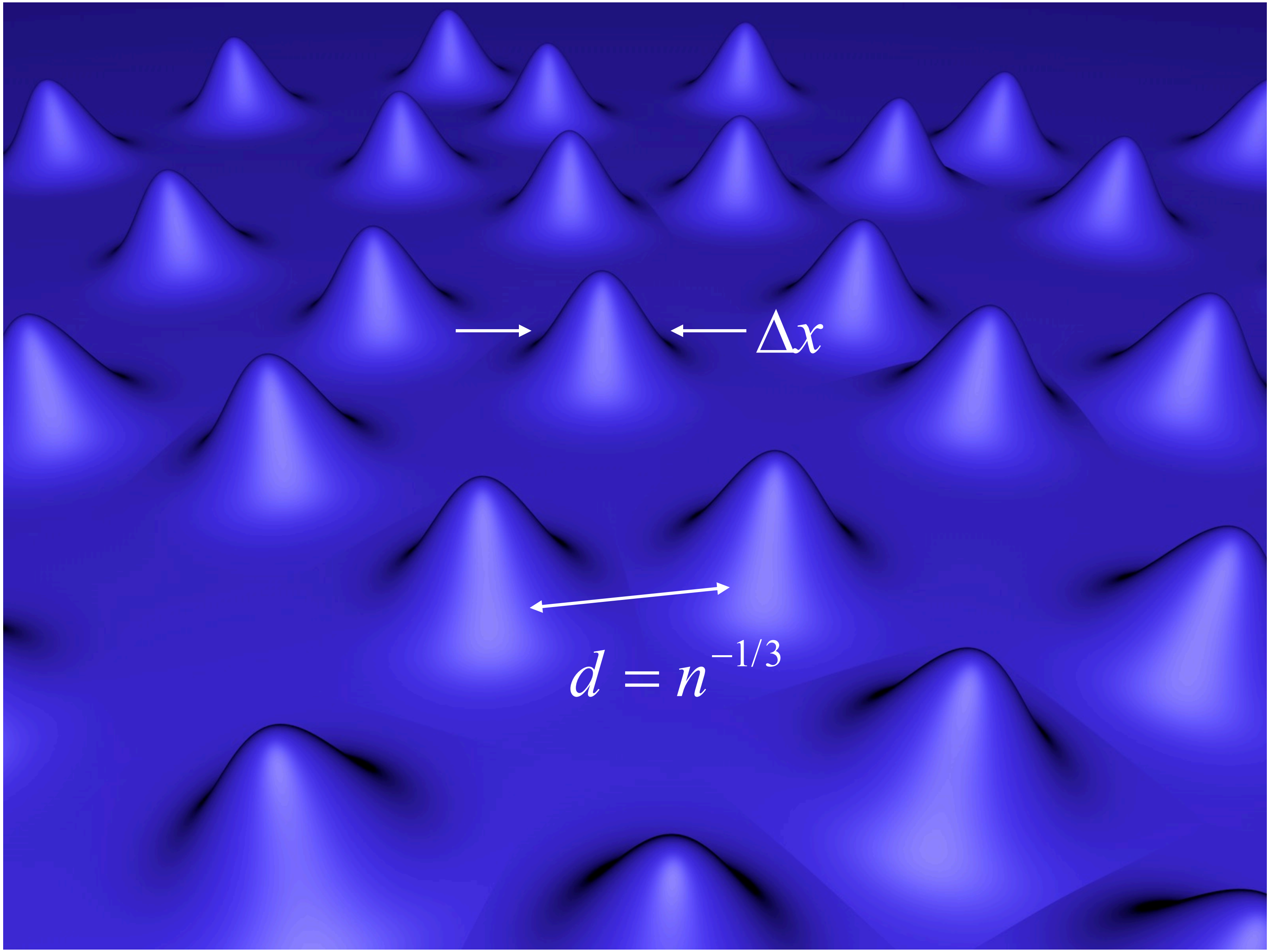
Particles...



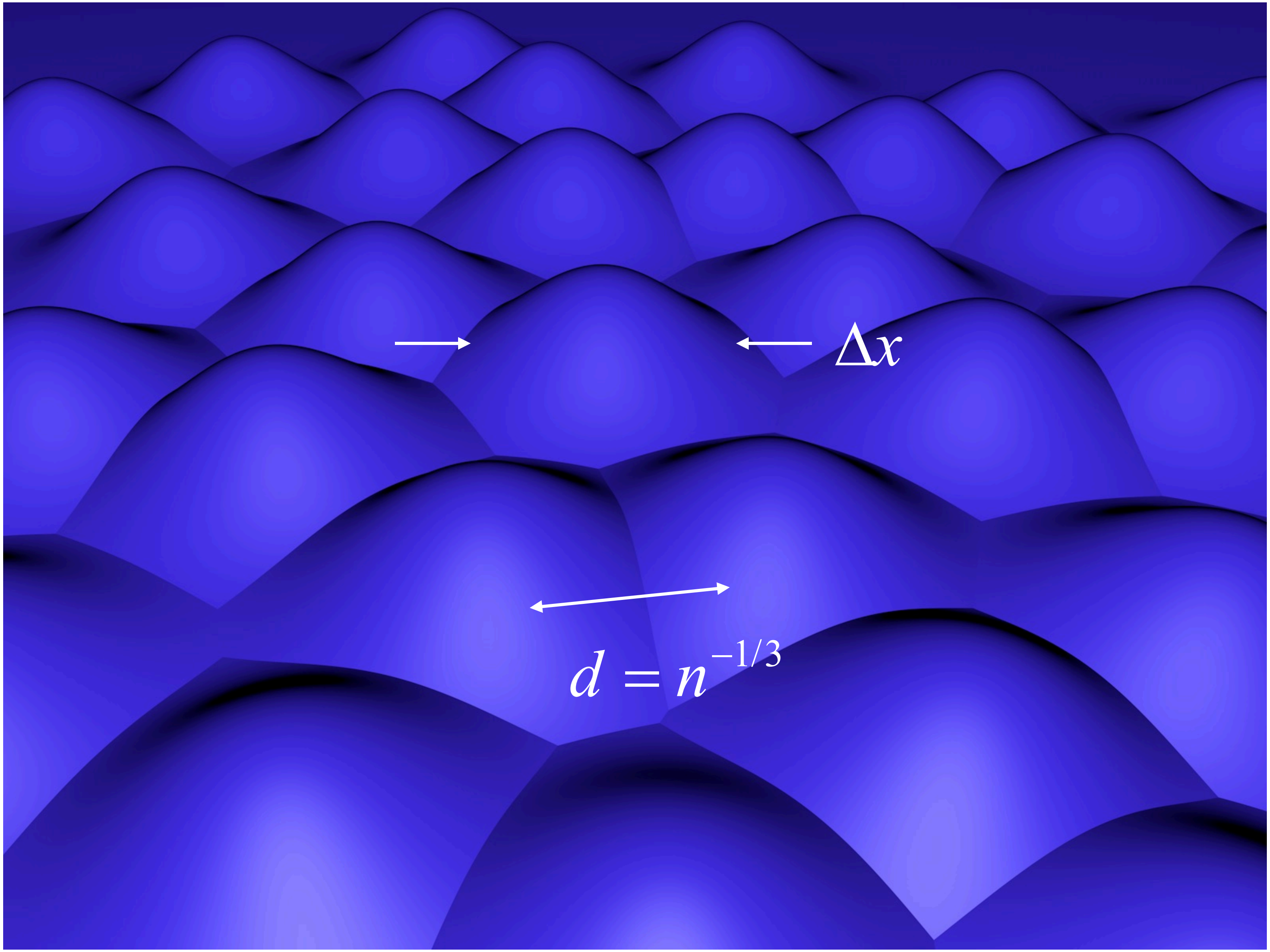
...behave as waves



When does wave mechanics matter?



When does wave mechanics matter?



Bosons versus Fermions

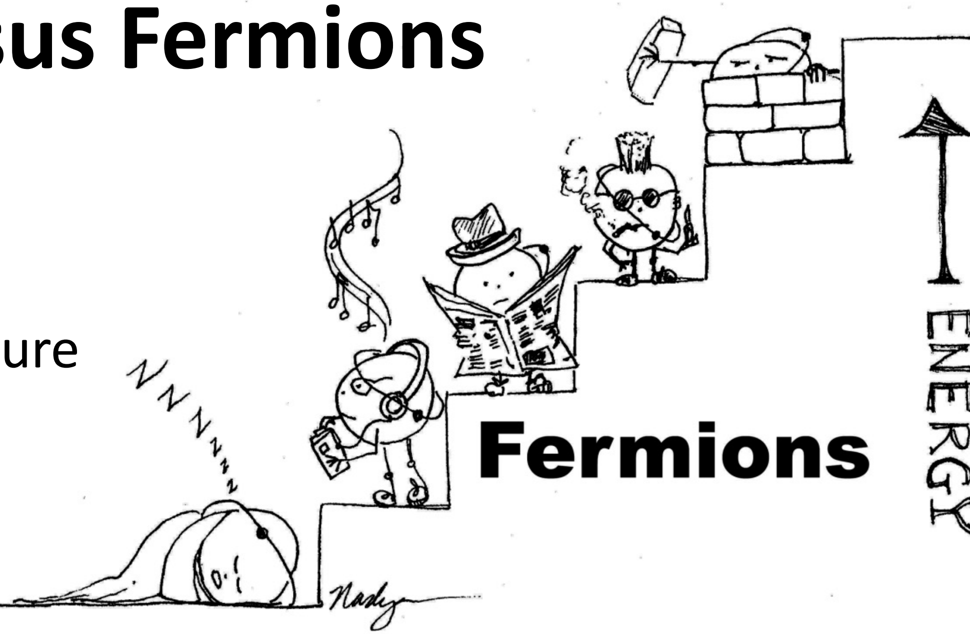
Fermions (unsociable):

Half-Integer Spin

Pauli blocking → Form Fermi sea

No phase transition at low Temperature

Fermi Feb. 1926
Dirac Oct. 1926



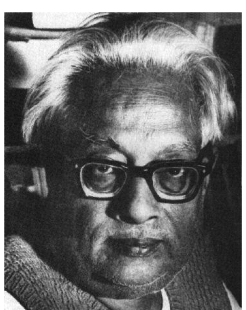
Bosons (sociable):

Integer Spin

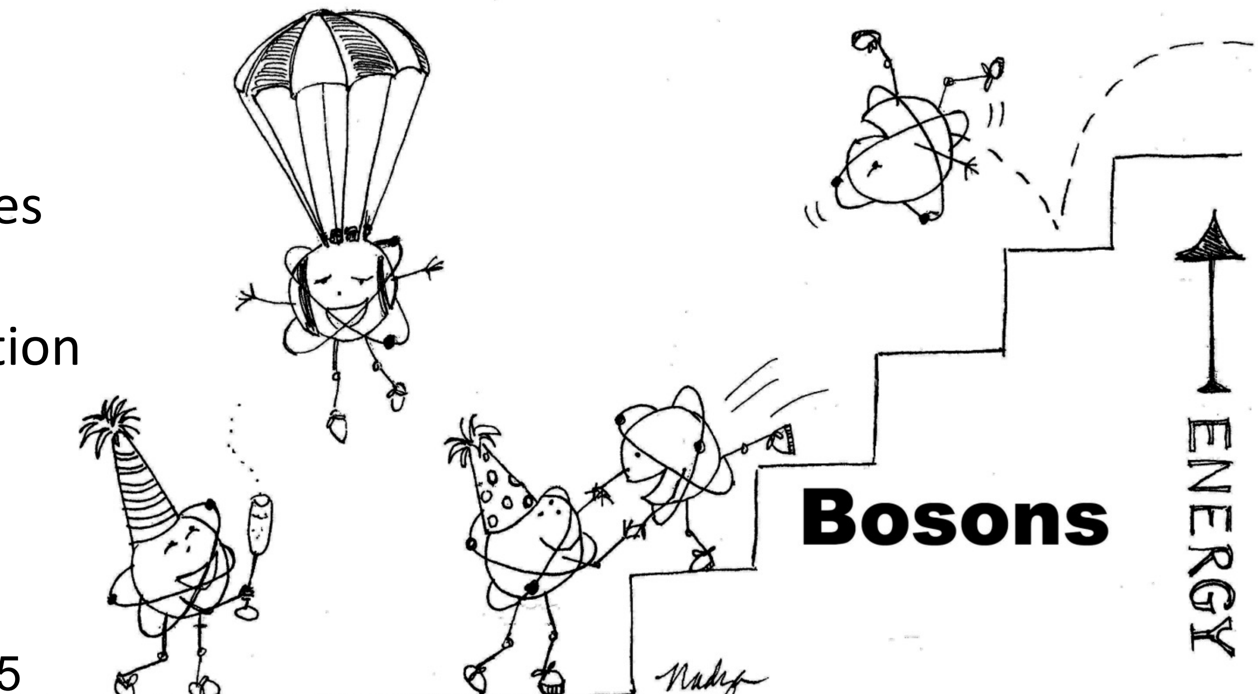
Can share quantum states

At low temperatures:

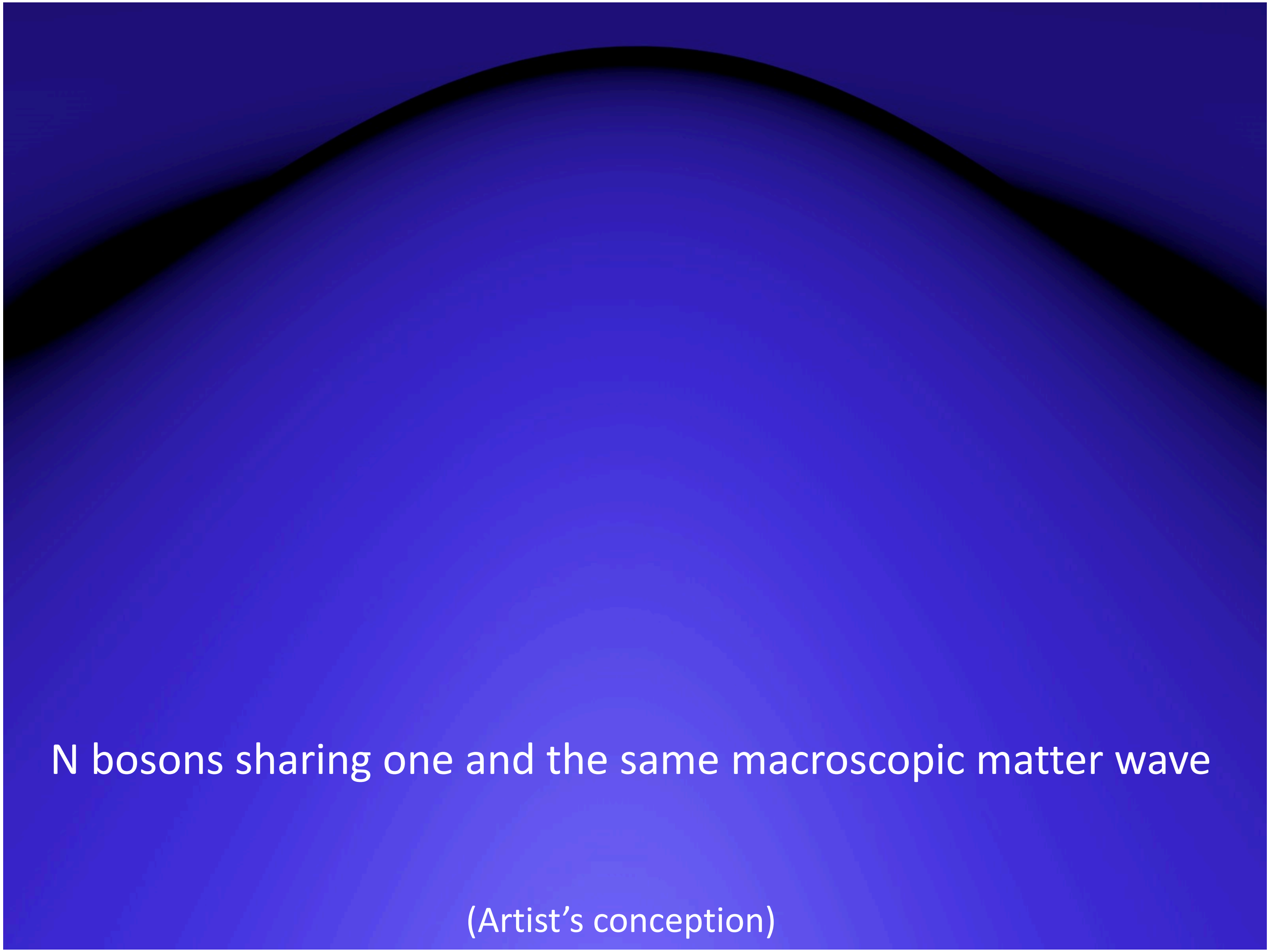
Bose-Einstein condensation



Bose 1924
Einstein 1924/25



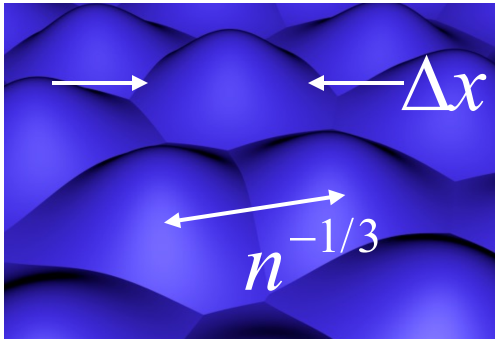
Bosons


N bosons sharing one and the same macroscopic matter wave
(Artist’s conception)

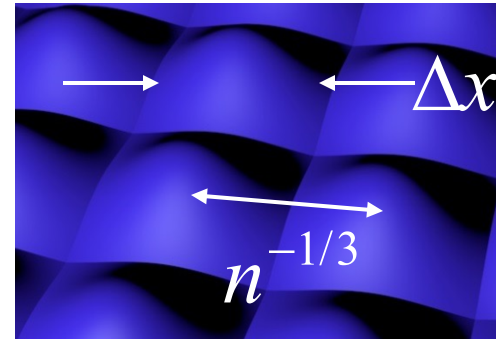
Fermions

Condition for quantum degeneracy

Position uncertainty ~ Interparticle spacing

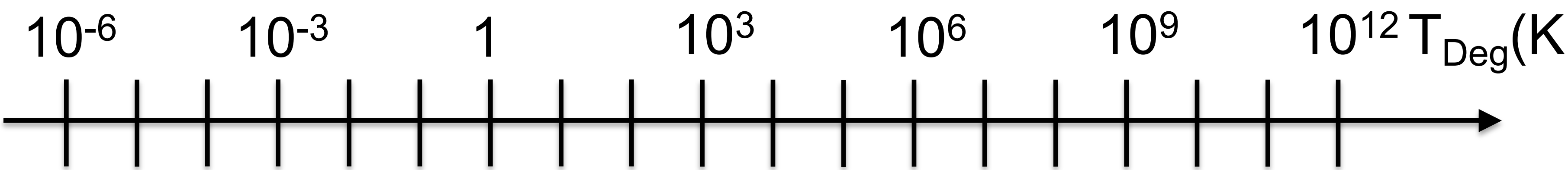


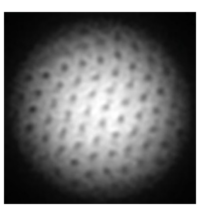
$$\Delta x = \frac{\hbar}{\Delta p} \approx n^{-1/3}$$



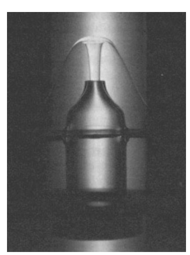
$$k_B T_{\mathrm{Degeneracy}} \approx \frac{\hbar^2}{m} n^{2/3} \approx E_F$$

Fermi energy





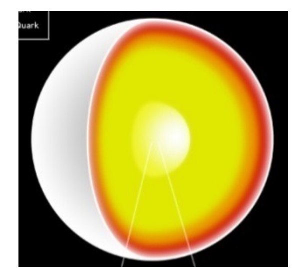
Ultracold
atomic gases



Liquid Helium

Metals

White dwarf



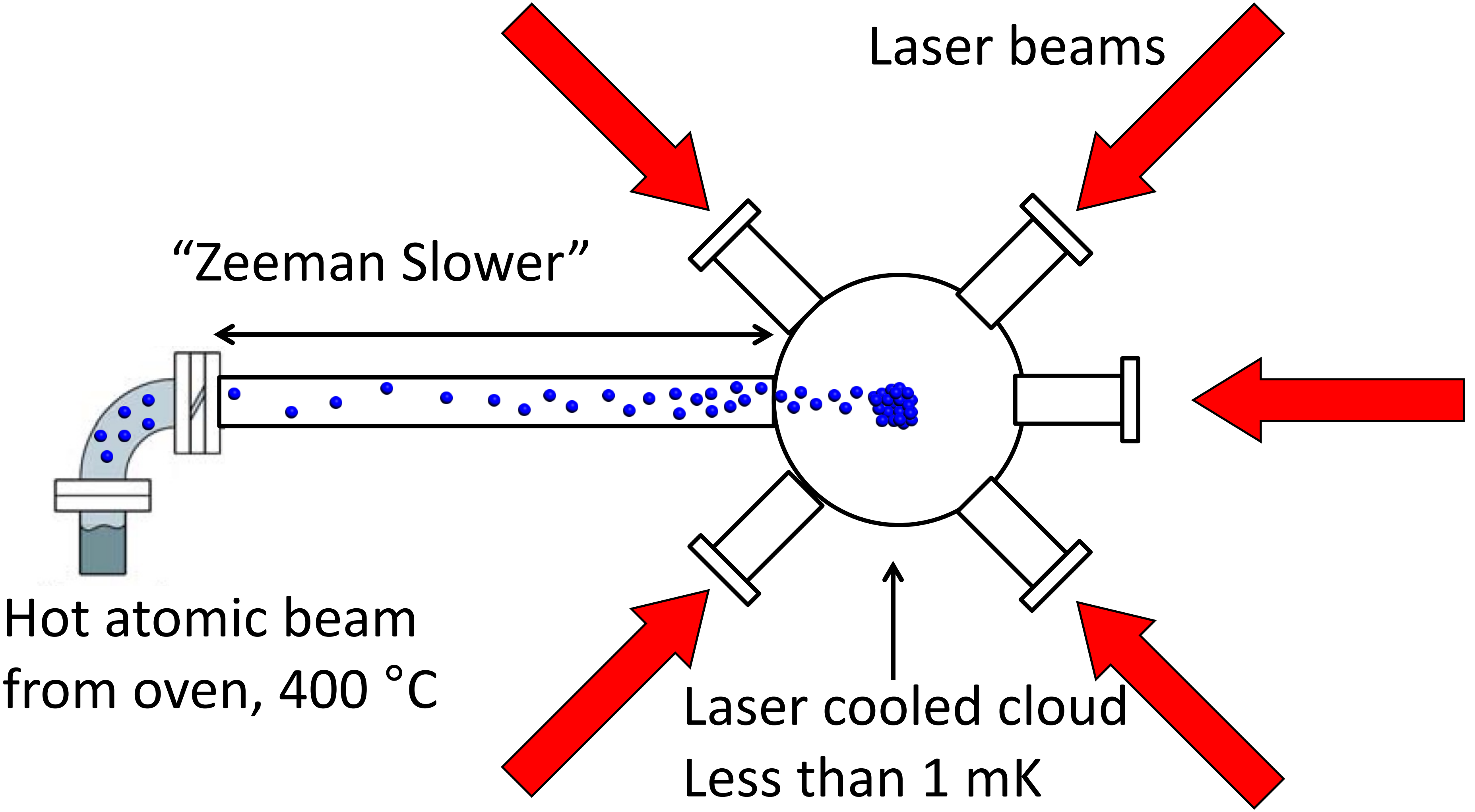
Neutron star

The cooling methods

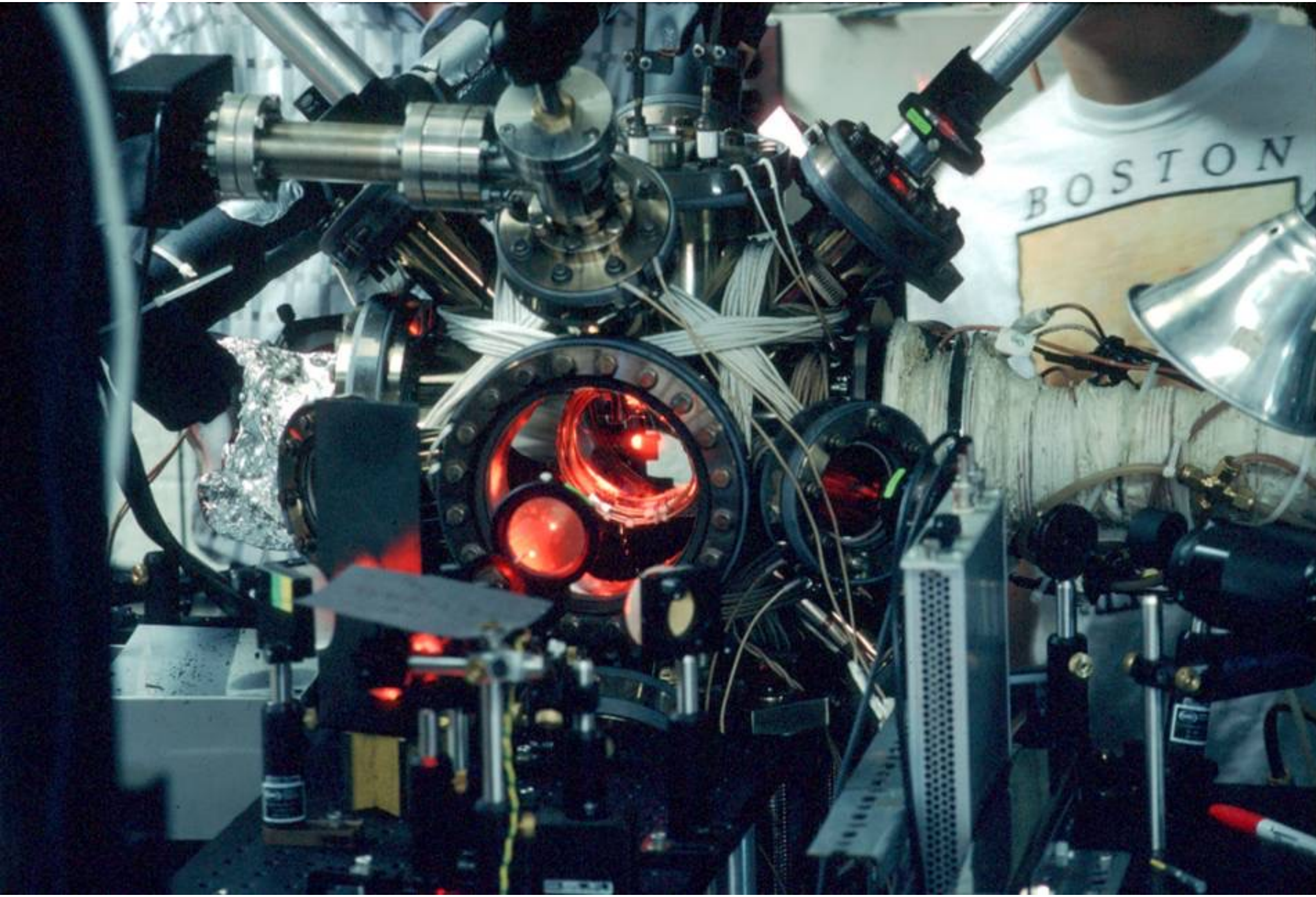
- Laser Cooling → ~ 1 mK

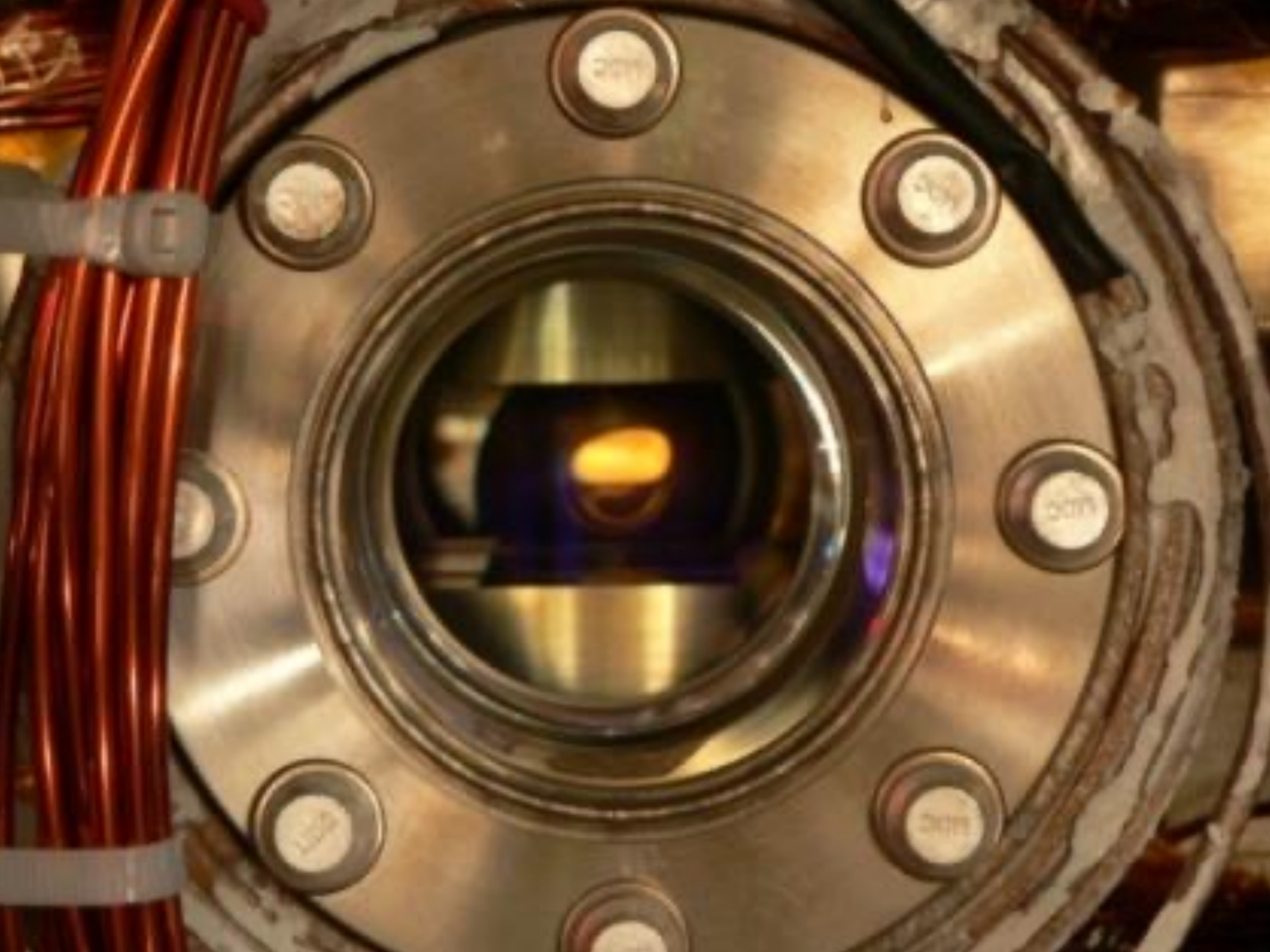
- Evaporative Cooling → ~ 10 nK

Laser Cooling



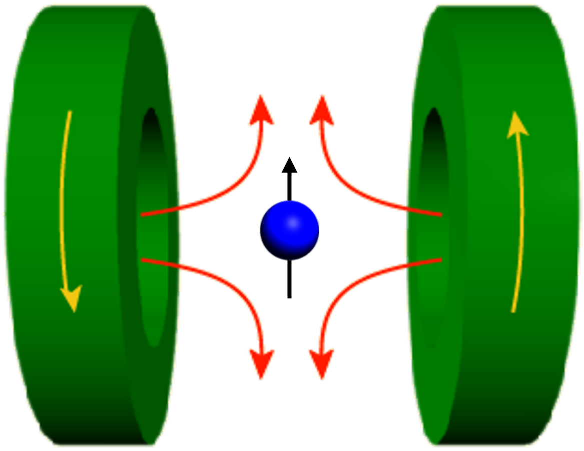
Chu, Cohen-Tannoudji, Phillips, Pritchard, Ashkin, Lethokov, Hänsch,
Schawlow, Wineland …

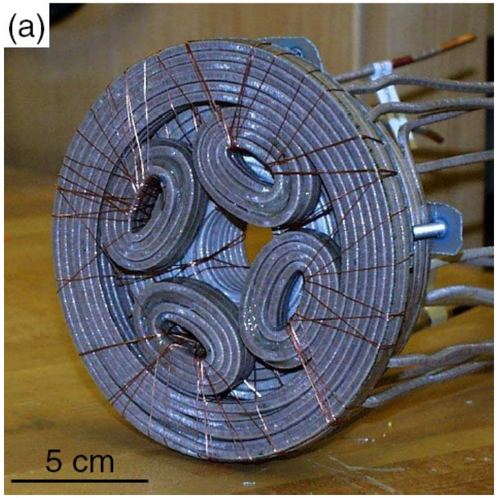

BOSTON



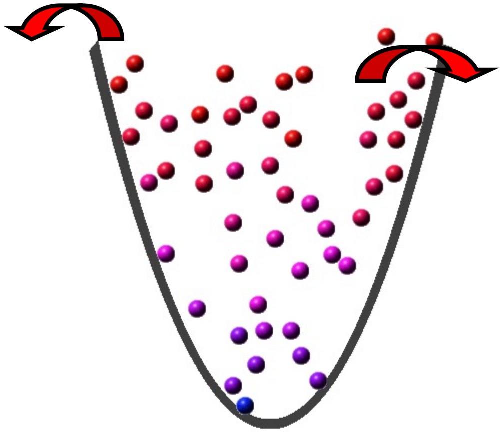
Techniques

Magnetic Trapping





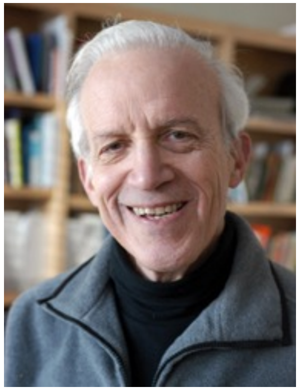
Evaporative Cooling



Evaporative Cooling

First invented and
demonstrated for
Spin-polarized hydrogen
@ MIT Hydrogen group
Kleppner, Greytak
Idea: Harold Hess, 1986
1st Evaporation of hydrogen: 1988
RF-evaporation: Pritchard, 1989
Alkalis: Ketterle and Cornell, Wieman 1995

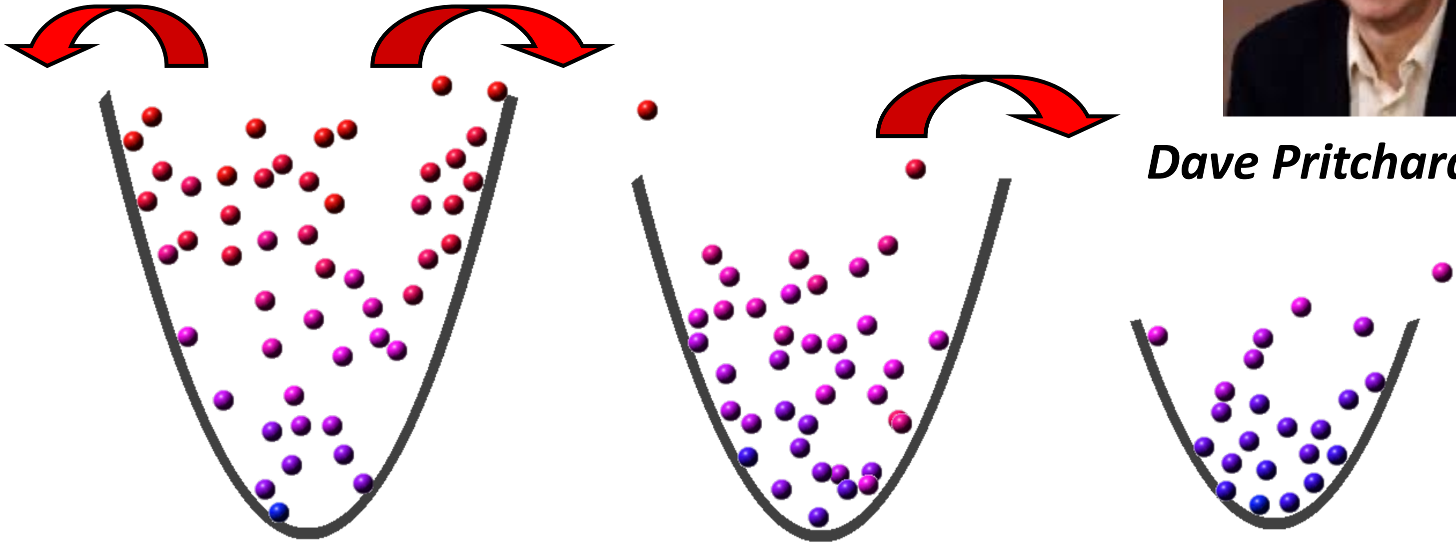
Tom Greytak



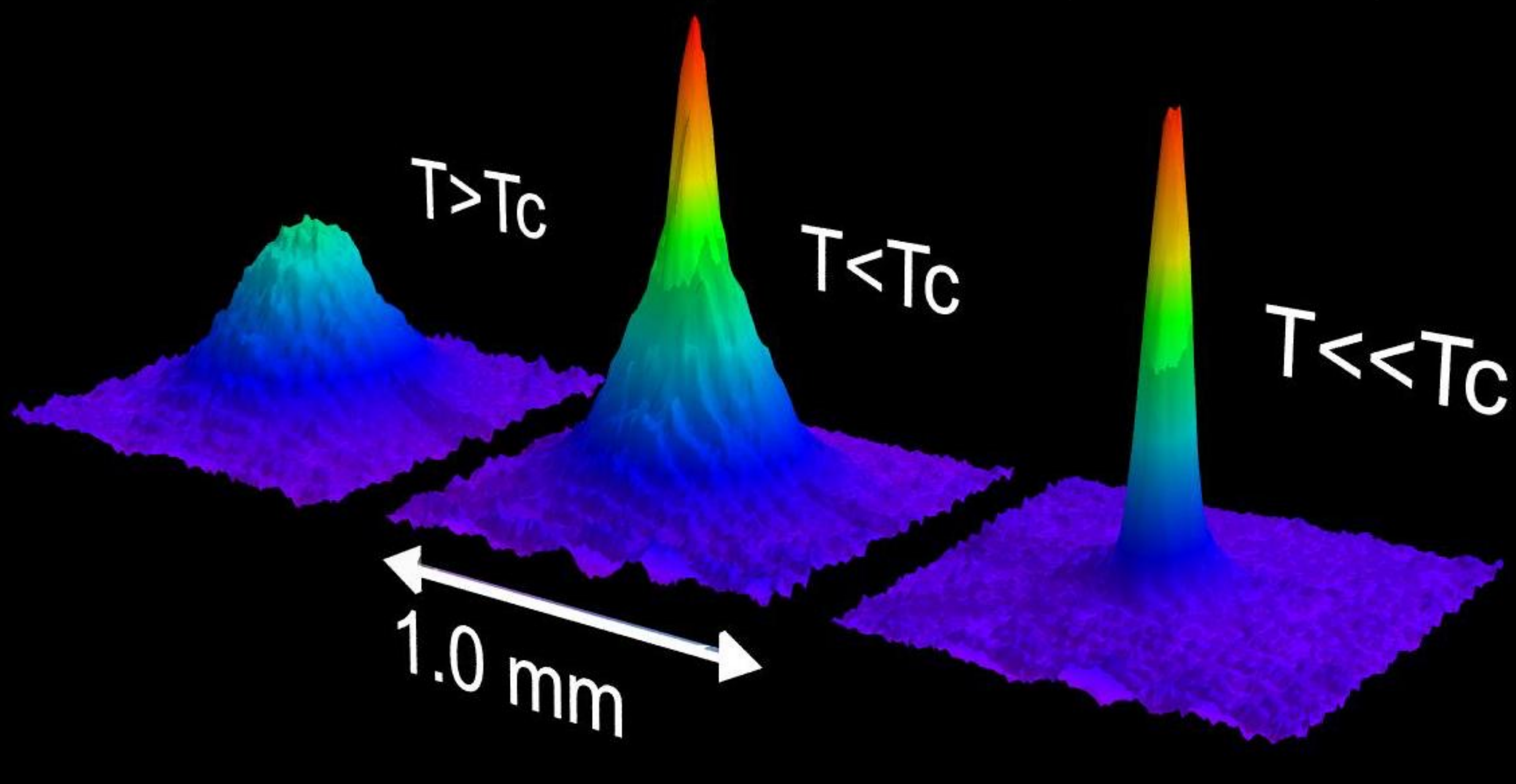
Dan Kleppner

Dave Pritchard

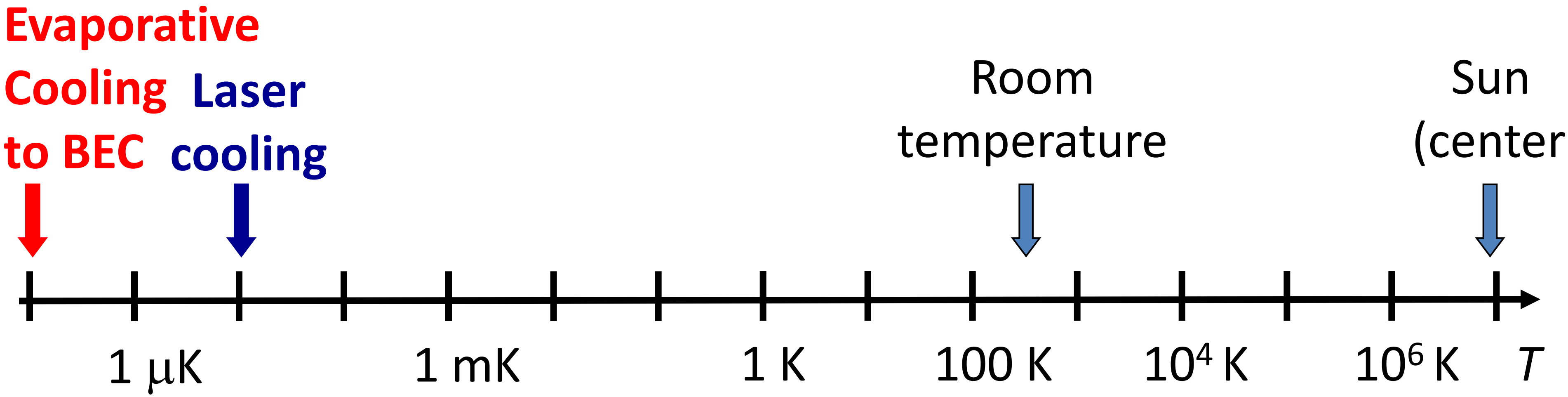
Wolfgang Ketterle



BEC @ MIT, 1995 (Sodium)



The cooling methods on the temperature scale



Nobel Prize 2001
E. Cornell, W. Ketterle, C. Wieman

Nobel Prize 1997
S. Chu, C. Cohen-Tannoudji, W. Phillips

30 s in the life of an atom cooler

0 s → 30 s time

Loading Magneto-Optical Trap
NP 1997
From an Atomic Beam
NP 1943
O. Stern
via a Zeeman Slower
NP 1901
Lorenz & Zeeman
NP 1997
B. Phillips
Using lasers
NP 1964
Townes, Basov&Prokhorov
& laser spectroscopy
NP 1981
Bloembergen, Schawlow

Optical Molasses
NP 1997
S. Chu
"Sisyphus Cooling"
C. Cohen-Tannoudji

Optical Pumping
NP 1966
A. Kastler
+
Hyperfine Purification via Rabi flop
NP 1944
I.I. Rabi
NP

Magnetic Trapping
Trapping of ions:
NP 1989
W. Paul
H. Dehmelt

Evaporative Cooling to BEC
NP 2001
E. Cornell, C. Wieman, W. Ketterle
using RF magnetic resonance
NP 1944
I. I. Rabi
NP 1952
Bloch & Purcell

Examples of experiments with BEC / Cold Gases

• • • → 30 s … 35 s

Clock Shift measurements Via Ramsey Sequence
NP 1989
N. Ramsey

Cavity QED (with BEC)
NP 2012
S. Haroche

Feshbach Association & STIRAP to form ground-state molecules

Using Frequency combs
NP 2005
T. Hänsch, J. Hall

Raman Sideband Cooling (e.g. for single-site Imaging)
NP 2012
D. Wineland

A Brief History of Atomic Physics

Ref.: D. Kleppner, RMP 71, S78, 1999

Beginning of 20th century: Atomic Physics = core of physical sciences

What is known:

- Atoms exist (Mendeleev, spectral lines of elements, electrons, ions, e.m. origin of radiation by matter, … NP 1926 Perrin for "discontinuous structure of matter")
- Newtonian Mechanics, E&M well established, thermodyn. + Stat. Mech. to lesser extent

Problems:

- Heat capacities of gases
- Lack of real understanding of atoms
- Interpretation of spectral data

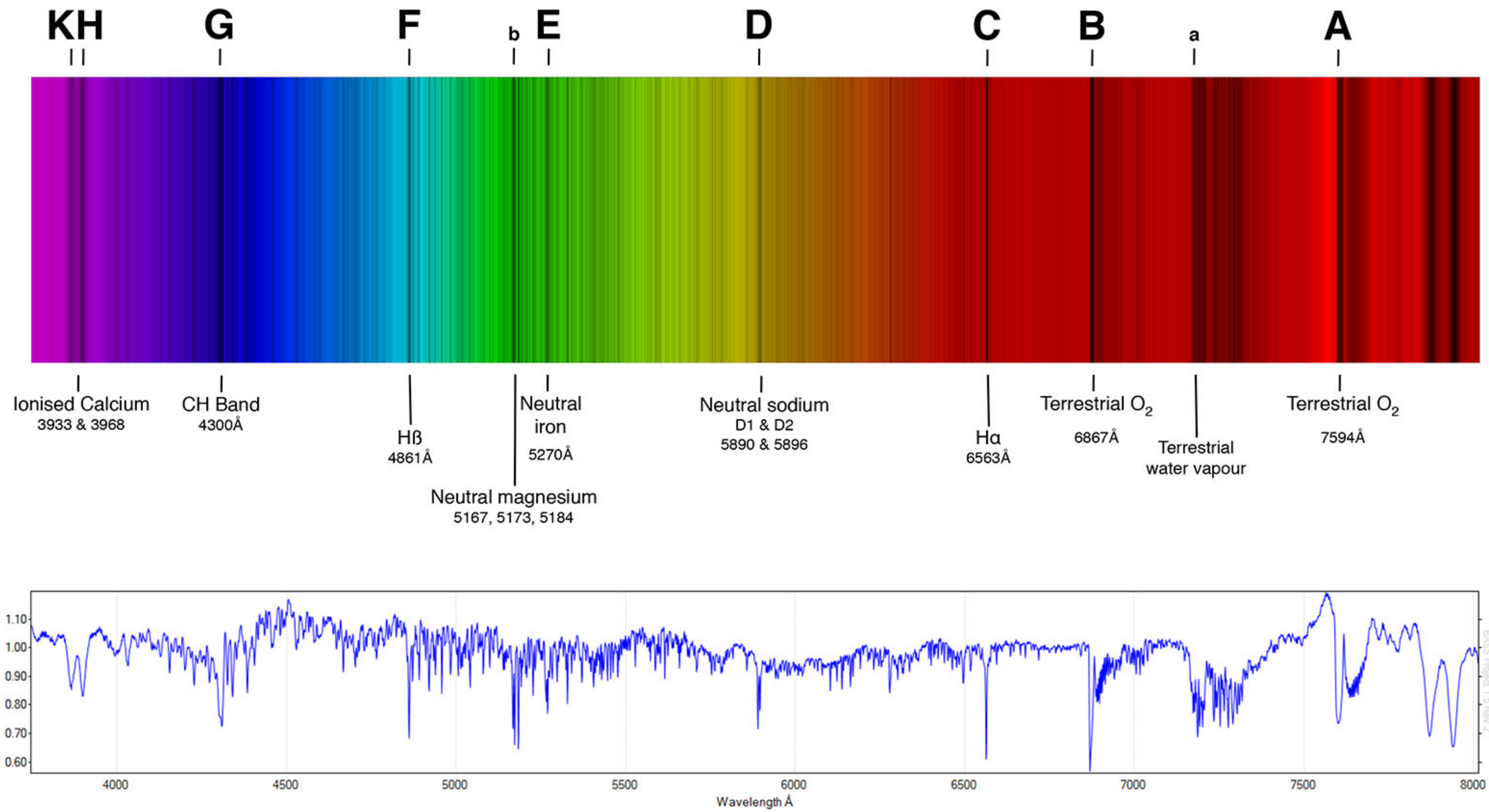
Revolution:

- Radioactivity
- X-rays
- Electrons
- Realization that stat. mech. f<u>ails</u> to describe a thermal radiation field

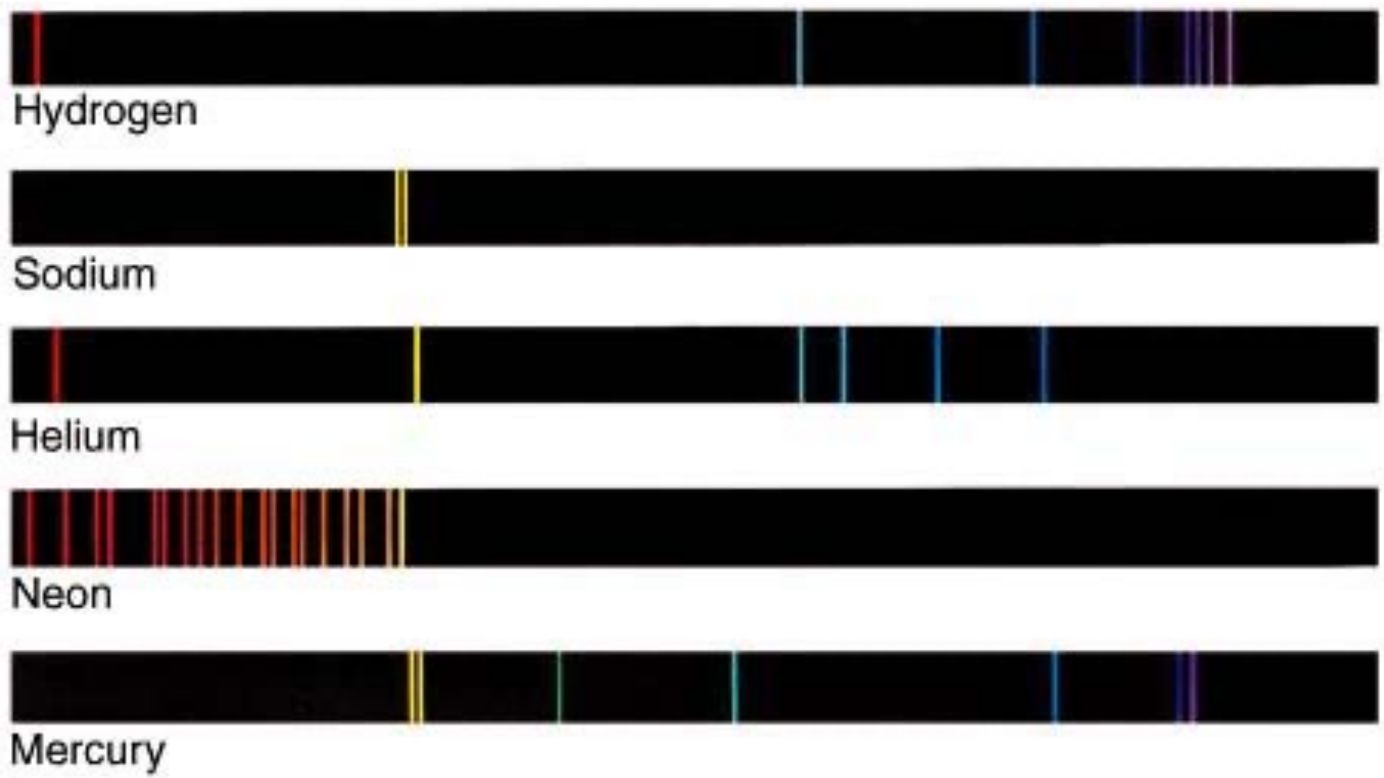
➔ Theories of Relativity, Gravitation by Einstein

➔ Quantum Mechanics: Planck, Einstein, Bohr, de Broglie, Heisenberg, Schroedinger, Dirac, Pauli, Born, …

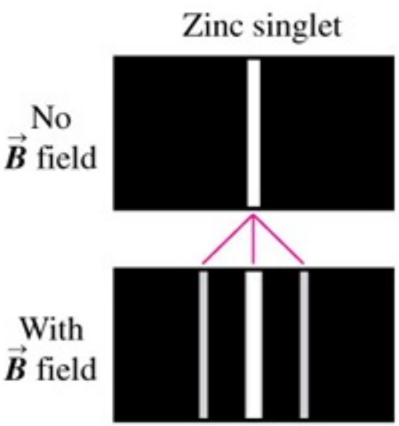
Fraunhofer Lines
(Joseph von Fraunhofer, 1787-1826)



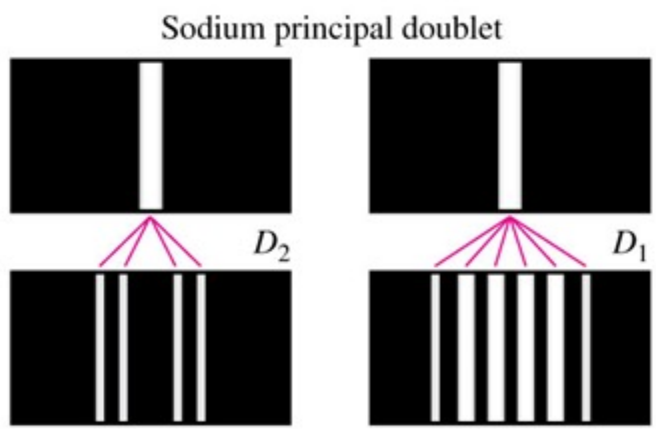
Retrieved from: Paul Luckas, http://jazzistentialism.com/blog/?p=1083


Hydrogen
Sodium
Helium
Neon
Mercury

Sodium Doublet – Fine Structure



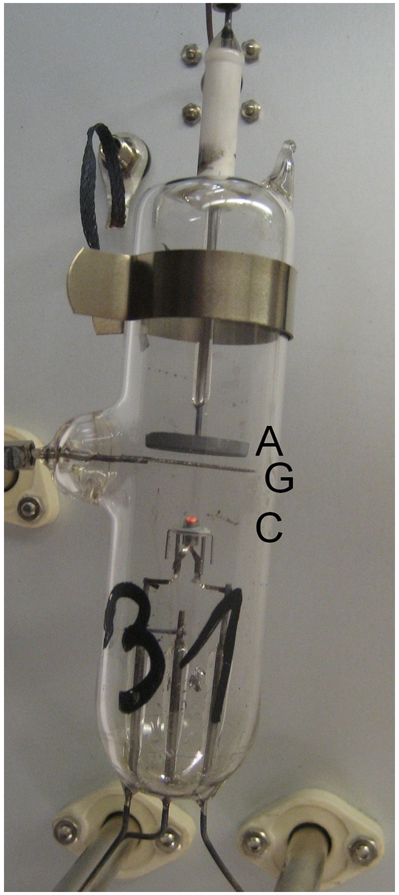
“Standard” Zeeman effect

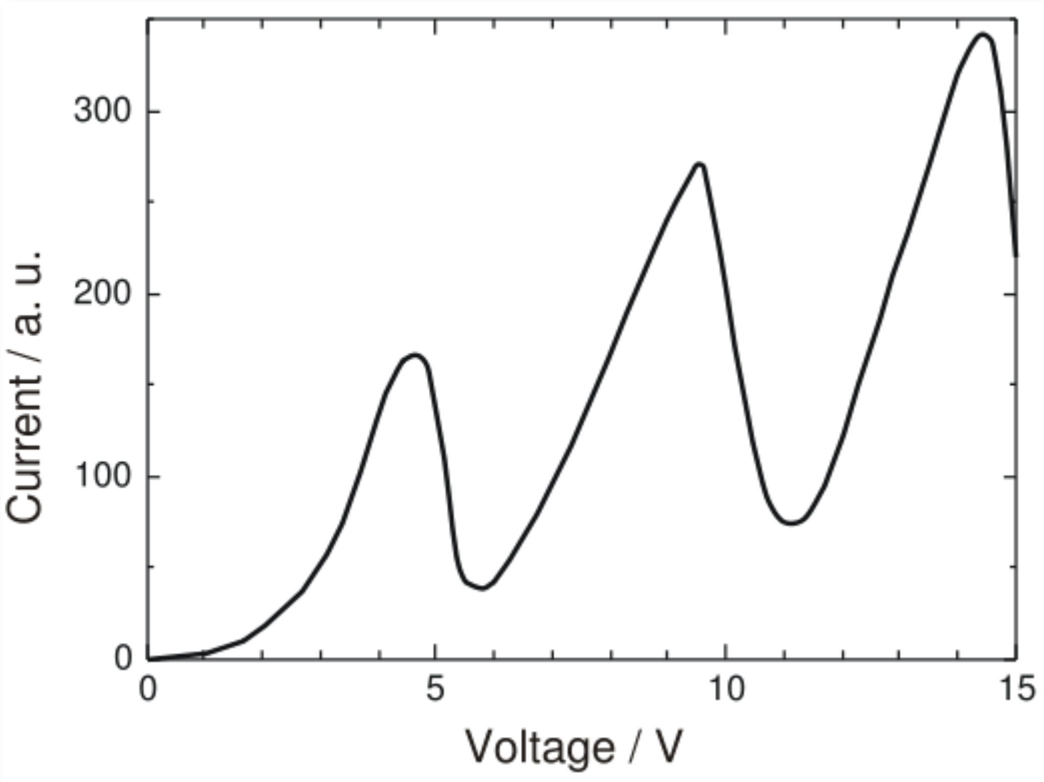


“Anomalous Zeeman effect”

Franck-Hertz experiment 1914

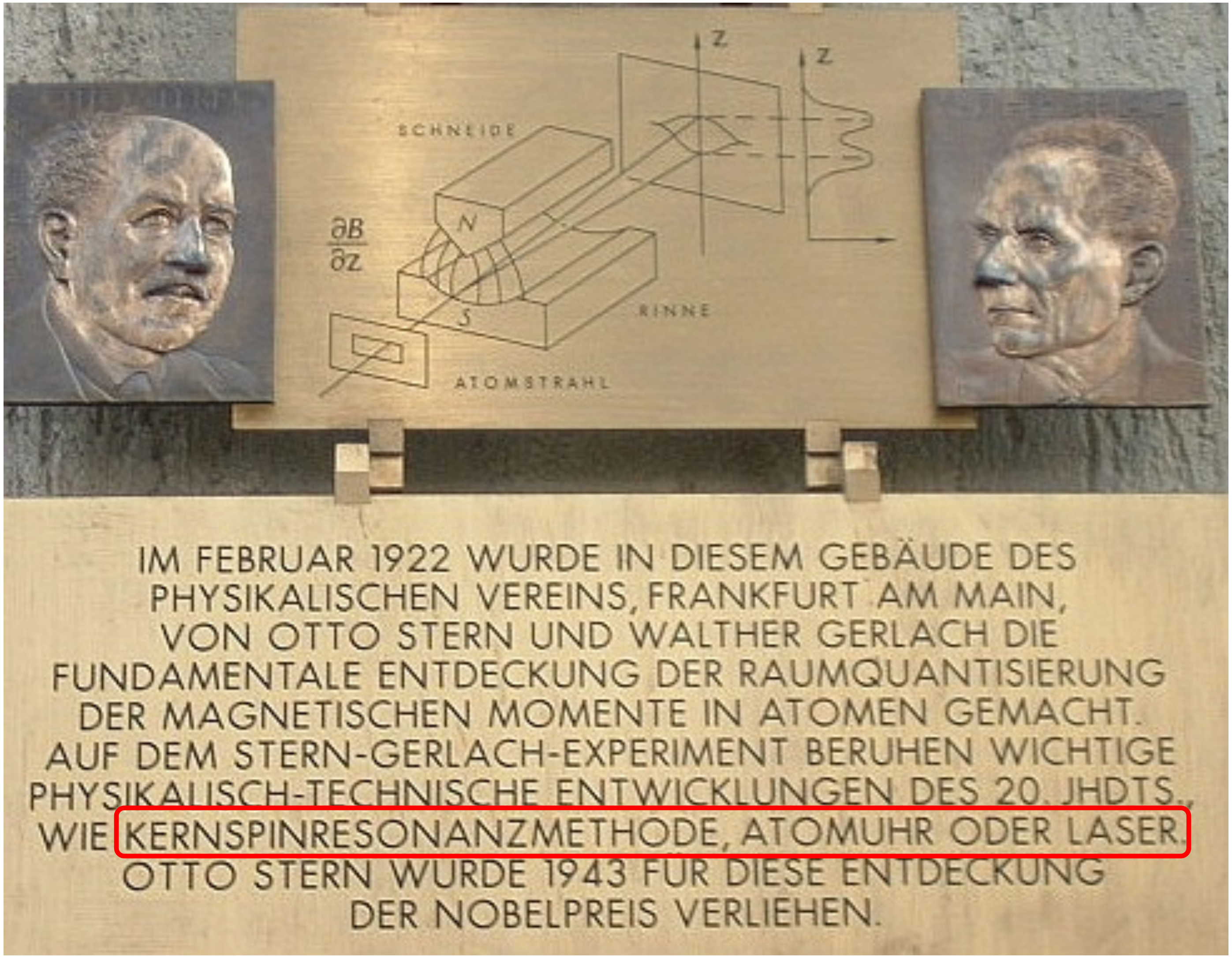
Quantization of energy levels
+ Emission of radiation with exactly the Bohr frequency $\frac{E_2 - E_1}{h}$





Stern-Gerlach experiment 1921

Magnetic moments are quantized



Plaque at the Physics Institute Frankfurt

June 1947: Shelter Island Conference

I. I. Rabi: Hyperfine structure of hydrogen too large by 1/1000 compared to Dirac theory

TABLE I. The hyperfine structure separation of H and D.

	Measured	Computed from Eq. (2)
νH	1421.3 ± 0.2 Mc	1416.90 ± 0.54 Mc
νD	327.37 ± 0.03 Mc	326.53 ± 0.16 Mc
$\nu H/\nu D$	4.3416 ± 0.0007	4.3393 ± 0.0014

Phys. Rev. 71, 914 (1947)

Breit: e^- has anomalous magnetic moment?

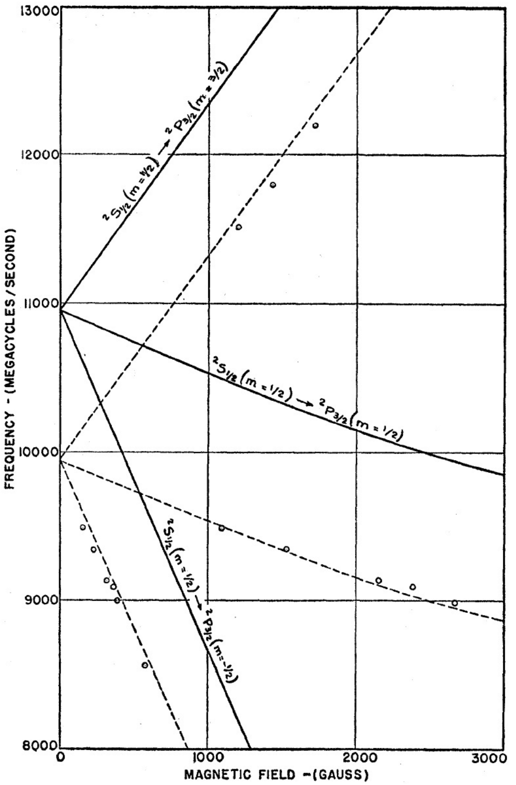
P. Kusch experiments: Yes, it's anomalous!

TABLE X. Observed ratios of atomic g values and the corresponding values of δ_S.

Experimental ratio	δ_S
$g_J(^2P_{3/2}\mathrm{Ga})/g_J(^2P_{\frac{1}{2}}\mathrm{Ga}) = 2(1.00172 \pm 0.00006)$	0.00114 ± 0.00004
$g_J(^2S_{\frac{1}{2}}\mathrm{Na})/g_J(^2P_{\frac{1}{2}}\mathrm{Ga}) = 3(1.00242 \pm 0.00006)$	0.00121 ± 0.00003
$g_J(^2S_{\frac{1}{2}}\mathrm{Na})/g_J(^2P_{\frac{1}{2}}\mathrm{In}) = 3(1.00243 \pm 0.00010)$	0.00121 ± 0.00005

Phys. Rev. 74, 250 (1948)

W. Lamb: There's a 3rd component in the fine-structure of hydrogen (Dirac: Should only be 2). $2^2S_{1/2}$ is higher than $2^2P_{1/2}$ by ~1 GHz! →



Phys. Rev. 71, 914 (1947)

➔ Dirac theory fails!

➔ Q E D Schwinger, Feynman, Tomonaga (NP 1965)

Magnetic Resonance

I. I. Rabi 1933 — Magnetic Resonance Technique
NP 1944
→ measure magnetic moments by measuring a <u>frequency</u>
→ Observe atomic and molecular systems in <u>isolation</u>
→ CONTROL over internal states
→ Wealth of information on atomic + molecular structure
+ on nuclear properties (deuteron has quadrupole moment!)

N. Ramsey 1950 — Separated Oscillatory Field Technique
NP 1989
→ Opened way to study internal molecular interactions in H_2
→ Hyperfine structure in atoms
→ Cs atomic clock (Essen&Parry 1955)

Sensitive tests of QED: free e^-, hydrogen atom, helium, hydrogenlike ions, muonium (1960, Hughes), positronium (1952, M. Deutsch)

Bloch & Purcell 1946 — Nuclear magnetic resonance
→ Spins and magnetic moments of nuclei
→ Molecular structure, structure & dynamics of solids, liquids, gases
→ biological + medical applications, magnetic resonance imaging

Control over Photons and Atoms

C. H. Townes 1954 Stimulated emission of radiation (Einstein 1916)
Townes, Bosov & Prokhorov Ammonia Maser
NP 1964

→ Quantum optics, frequency standard, amplifier
→ 3K microwave background Penzias, Wilson 1965

Schawlow & Townes 1958 Principles of the Laser
T. Maiman 1960 First laser (Ruby cyrstal)
A. Javan & Bennett 1960 CW Laser (He-Ne)

A. Kastler 1966 Optical Pumping
NP 1966 → CONTROL of internal states of atoms + molecules

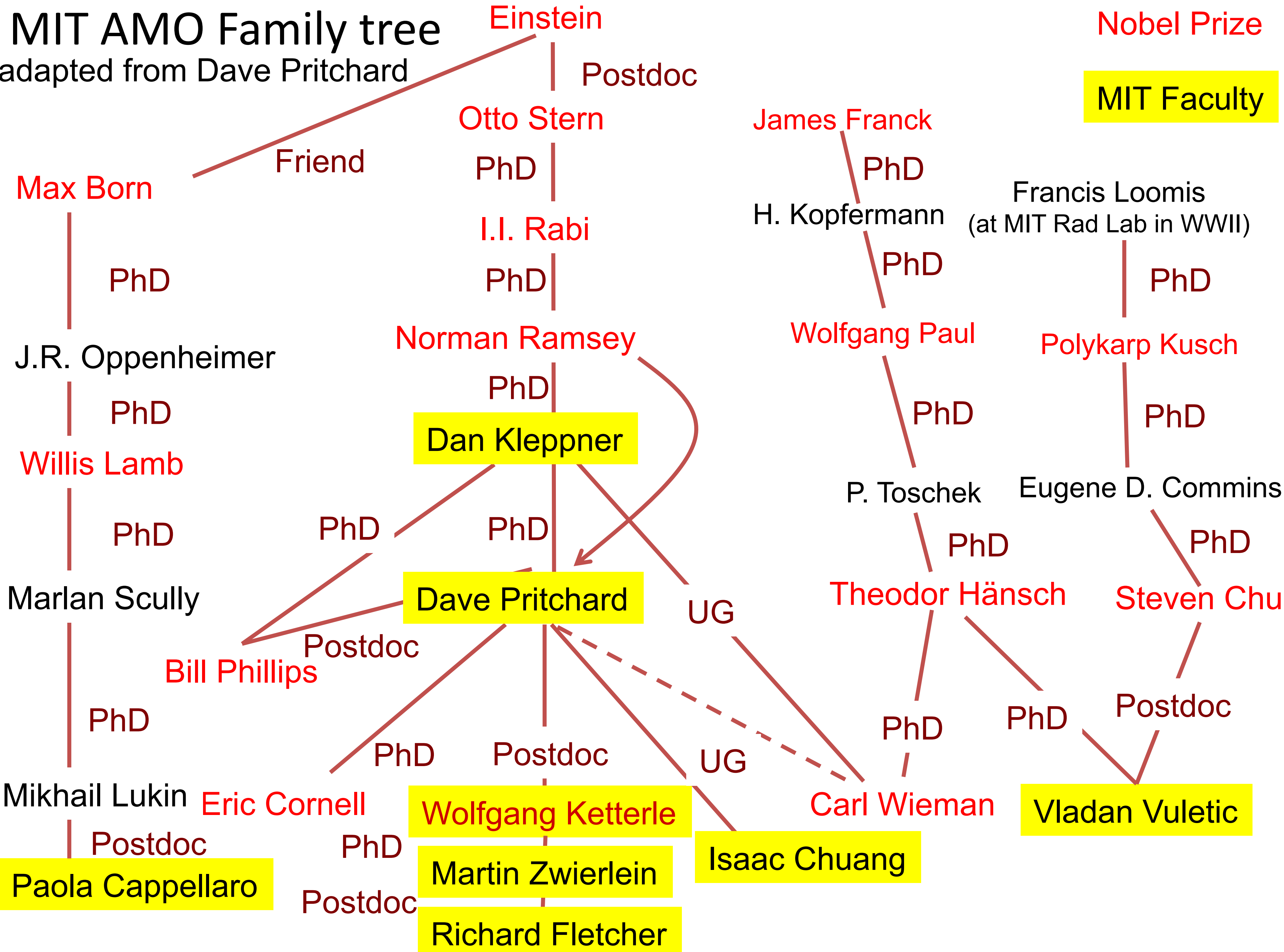
W. Paul 1953 Ion trap
NP 1989 → CONTROL over external motional degrees
→ Mass spectrometer

Nobel Prizes in Atomic/Photonic Control

	Spatial	Internal
1901 Lorenz&Zeeman		atomic spectra in gas
1907 Michelson	Interfere photon paths	
1943 *Stern*	Molecular Beams	
1944 *Rabi*		Two State Resonance
1952 Bloch & Purcell		NMR
1964 Townes, Basov&Prokhorov	Laser Beams	Maser & Laser
1966 Kastler		Optical Pumping
1981 Bloembergen&Schawlow		Laser Spectroscopy
1989 Dehmelt &Paul, *Ramsey*	Ion Trapping	Two State Superposition
1997 Chu, **Phillips**, Cohen-T.	Cooling & Trapping	
2001 **Cornell, Ketterle, Wieman**	BEC many atoms in one spatial - internal state	
2005 Hänsch, Hall, Glauber	Quantum Photons	Spectroscopy
2012 Wineland, Haroche	making, manipulating, measuring entangled states	

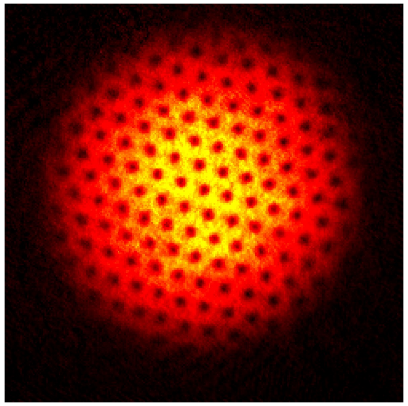
MIT AMO Family tree

adapted from Dave Pritchard



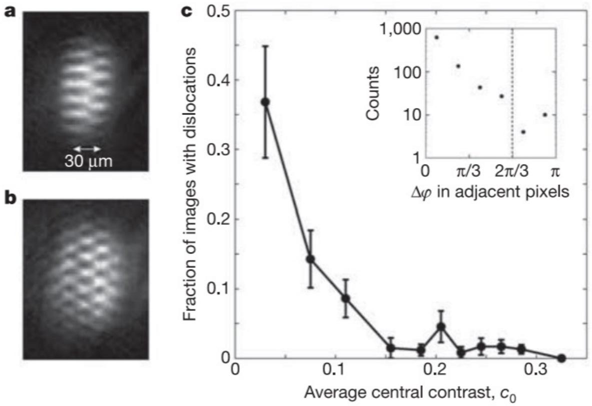
AMO in Modern Times

1995-today



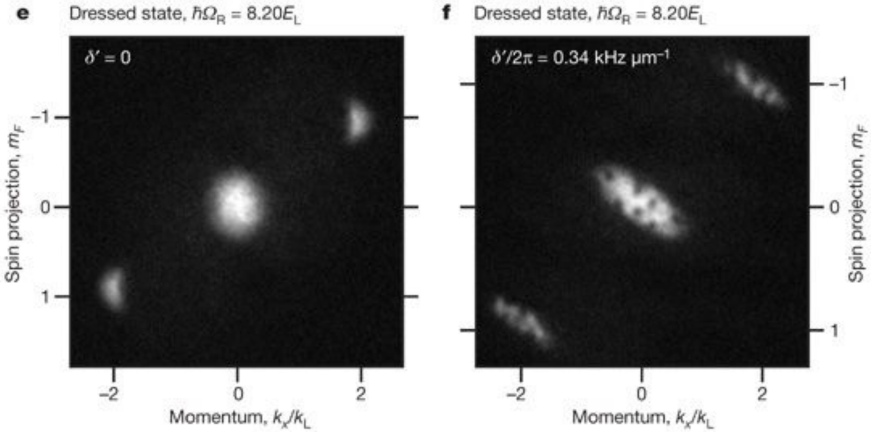
Studies of BECs
Rotation, Turbulence, Transport,
Impurities, Lower dimensions,

- 2006



Berezinskii-Kosterlitz-Thouless
Crossover,
Hadzibabic&Dalibard,
Nature 2006

- 2009



Artificial
Gauge Fields
Spielman,
Nature 2009

Studies on BECs (cont.): Turbulence

Hadzibabic, Nature 2016

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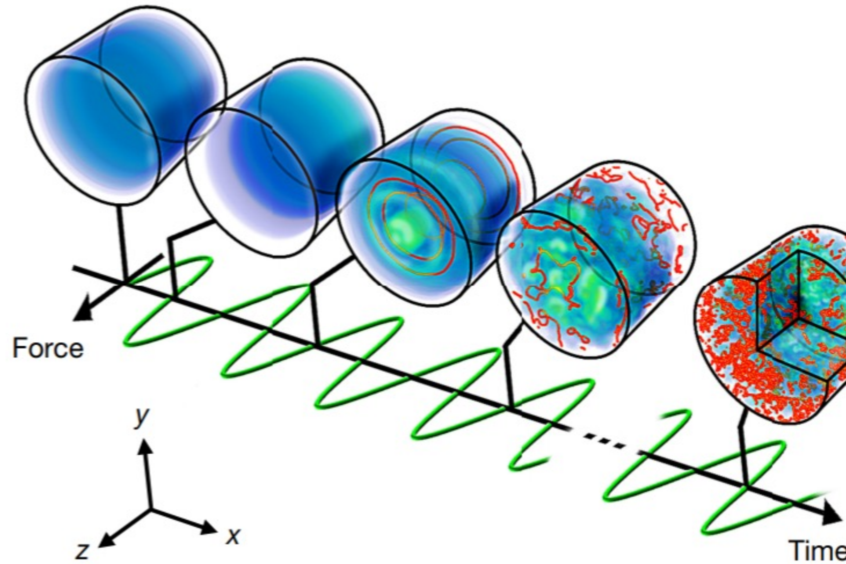

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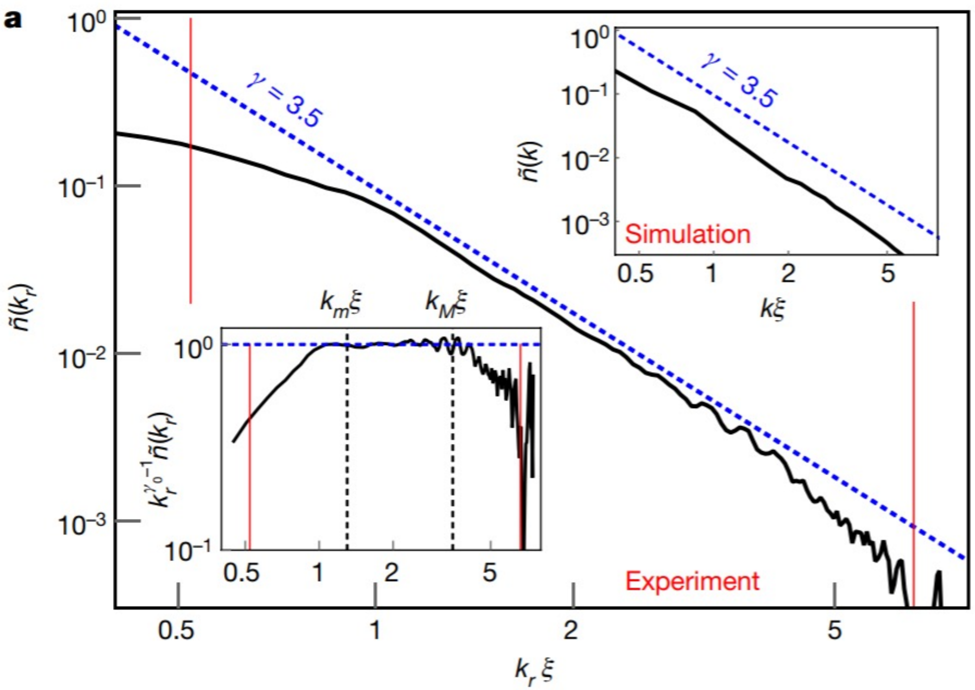
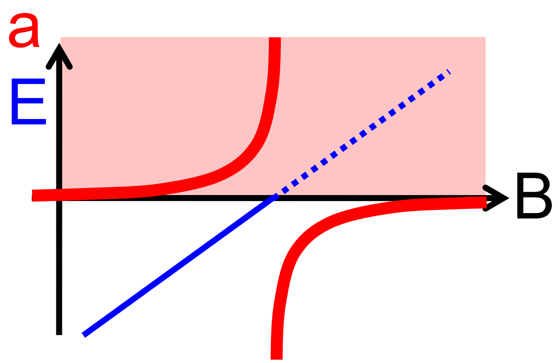
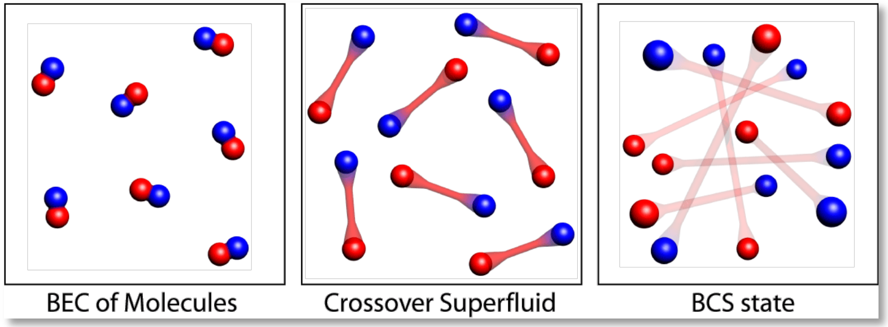


2001-now: strongly correlated states of matter

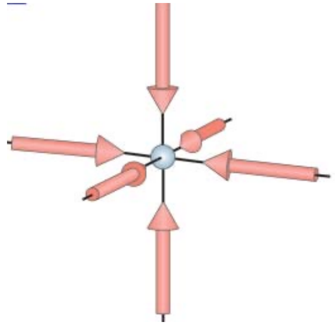
Feshbach Resonances → e.g. BEC-BCS Crossover

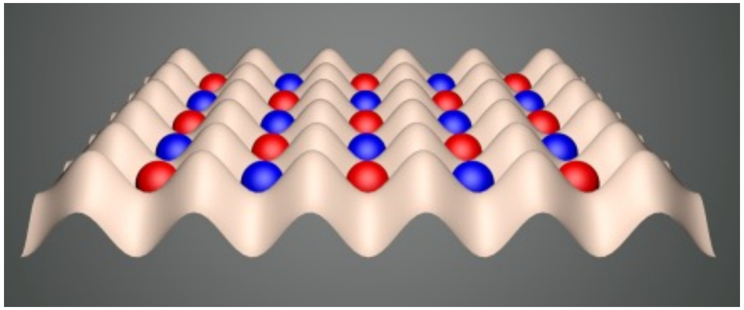




Quantum Gases → Quantum Fluids

Optical Lattices → e.g. Fermi-Hubbard model

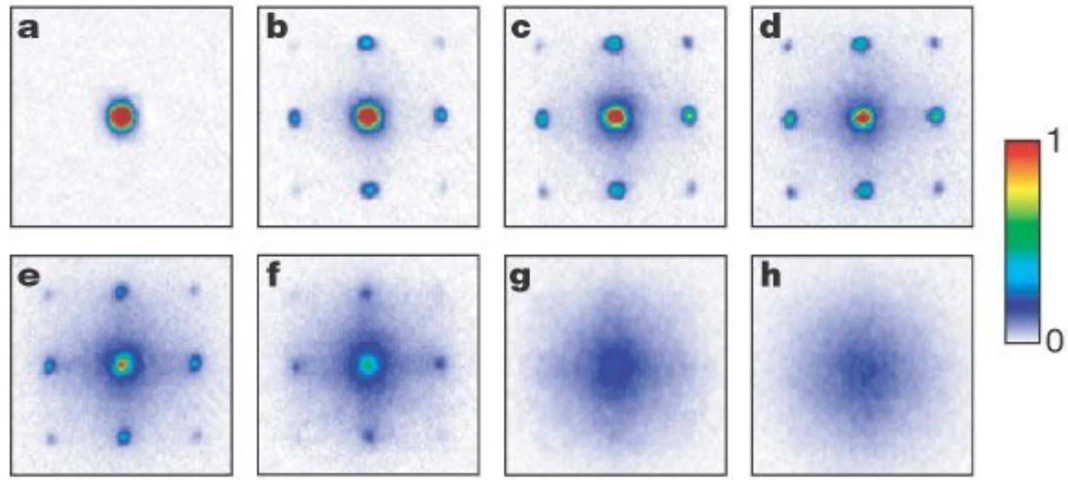




Quantum Gases → Quantum Solids

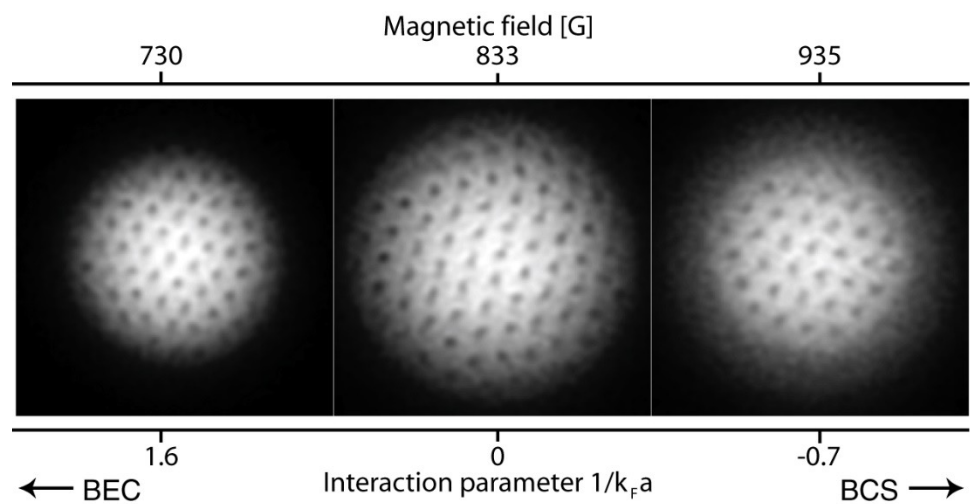
Strongly correlated states of matter

2001: Bosonic Mott Insulator



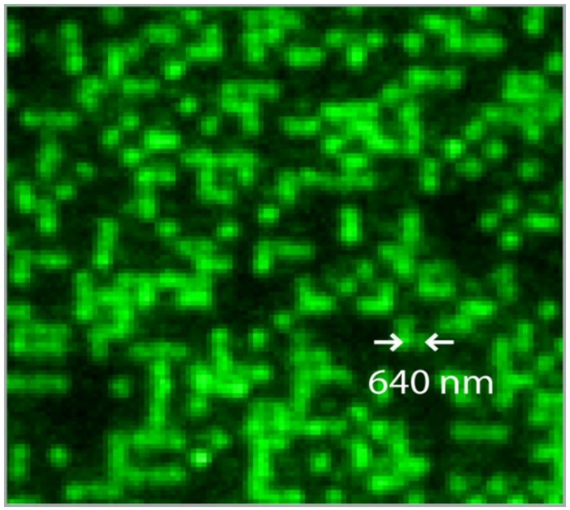
Greiner, Mandel, Esslinger, Hänsch, Bloch, Nature 2002

2005: Superfluidity in a Fermi gas

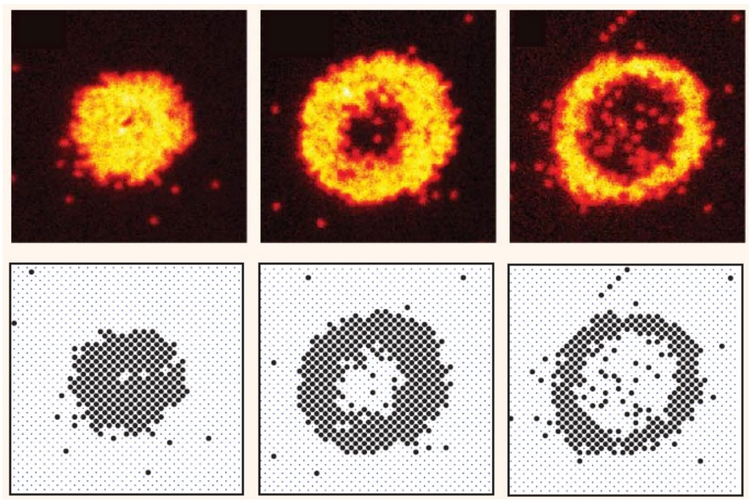


Zwierlein, Abo-Shaeer, Schirotzek, Schunck, Ketterle, Nature 2005

Quantum Gas Microscopes



Bosons
^{87}Rb



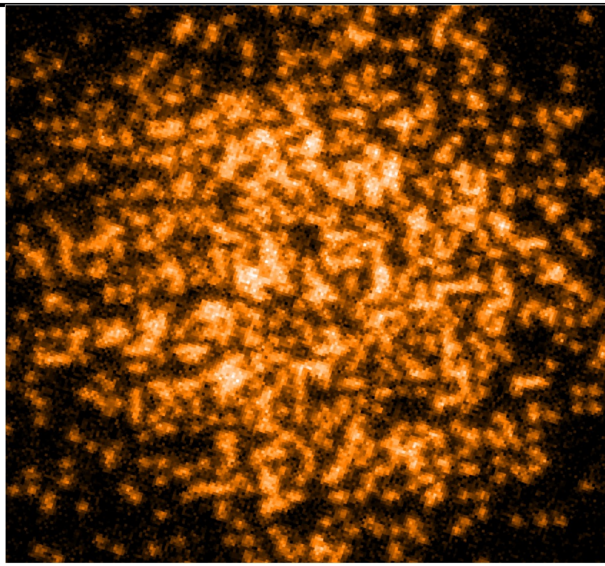
Bakr *et al.*, Nature 462, 74-77 (2009)

Sherson *et al.*, Nature 467, 68-71 (2010)

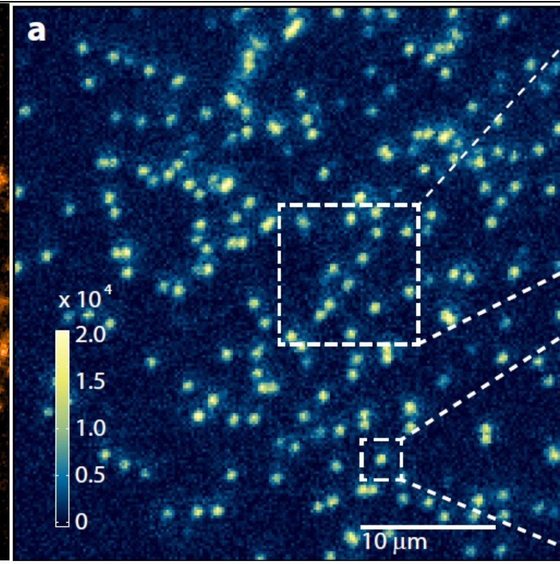
Also: ^{174}Yb bosons, Miranda et al., PRA 91, 063414 (2015)
Yamamoto et al., NJP 18, 023016 (2016)

Fermi Gas Microscopes

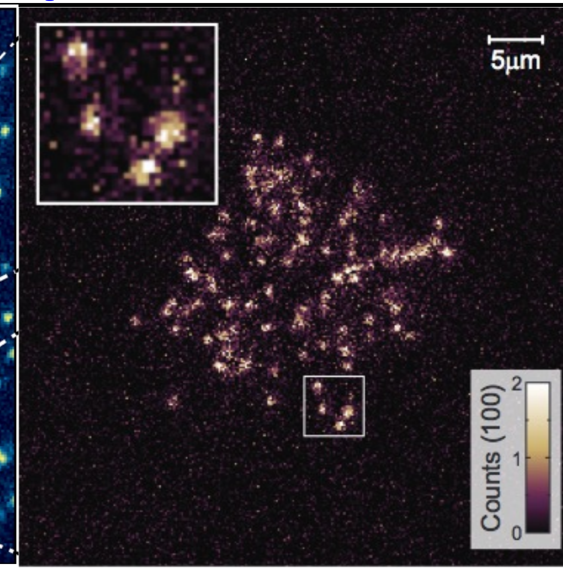
^{40}K



Zwierlein group, MIT
PRL **114**, 193001 (2015)

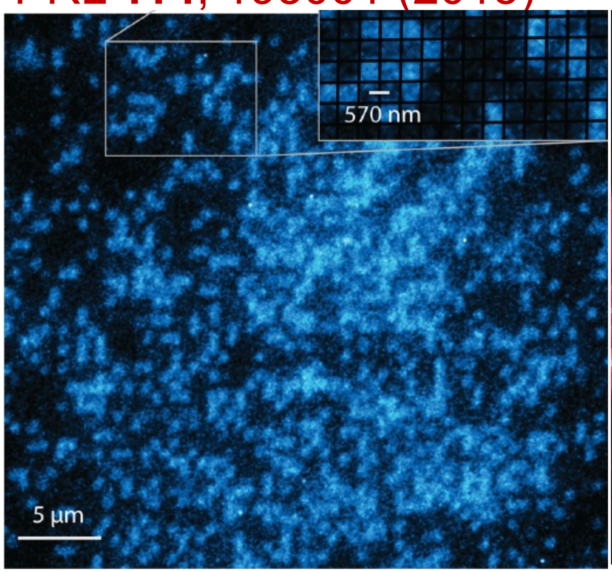


Kuhr group, Strathclyde
Nat. Phys. 11, 738 (2015)

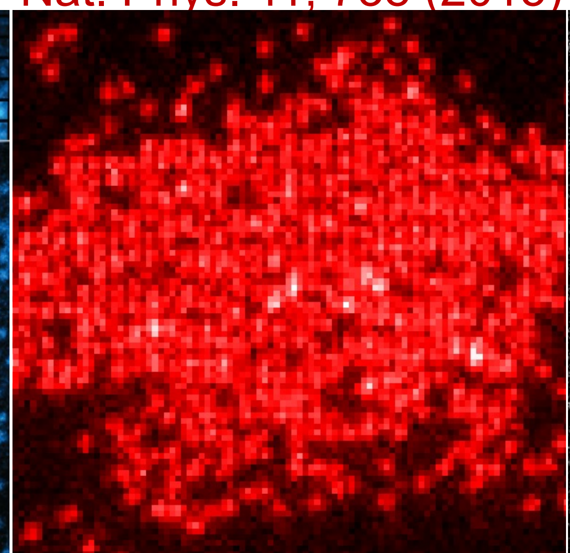


Thywissen group, Toronto,
PRA **92**, 063406 (2015)

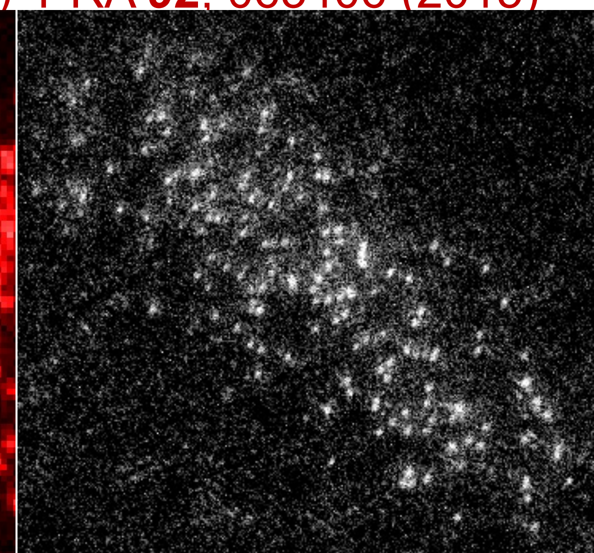
^{6}Li



Greiner group, Harvard
PRL **114**, 213002 (2015)



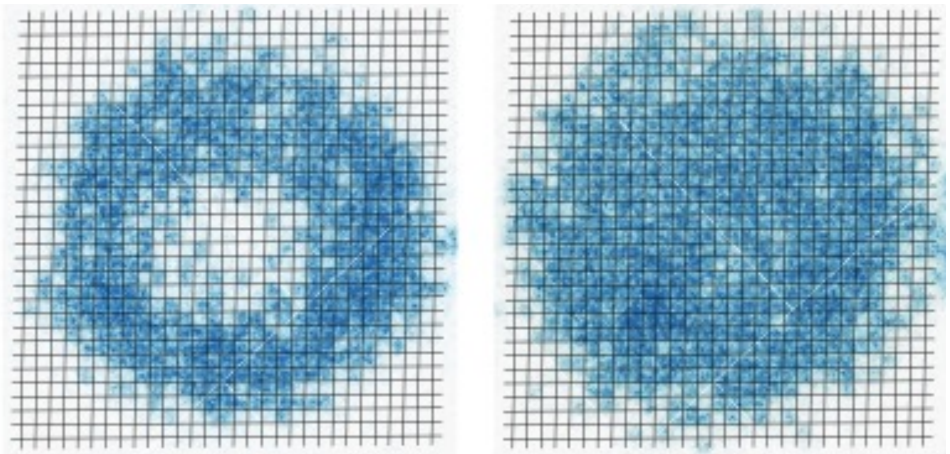
Gross/Bloch group, MPQ
PRL **115**, 263001 (2015)



Bakr group, Princeton
ultracold.princeton.edu

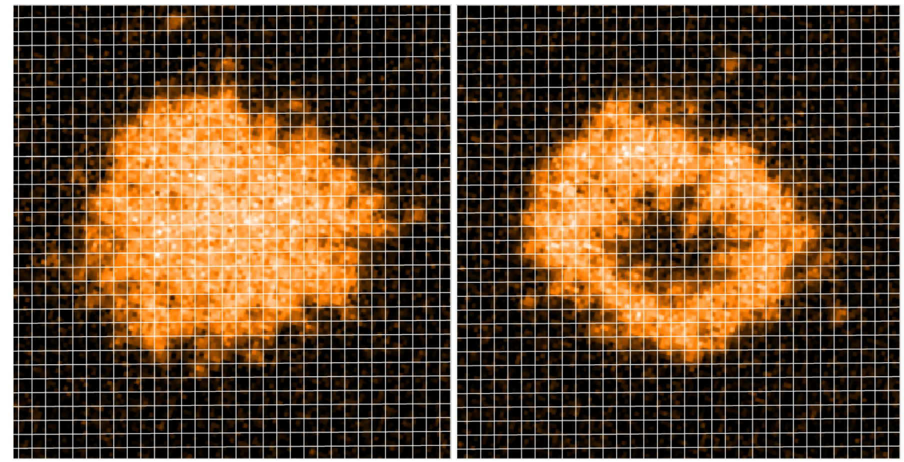
Fermionic Mott Insulators of ^{6}Li and ^{40}K

^{6}Li

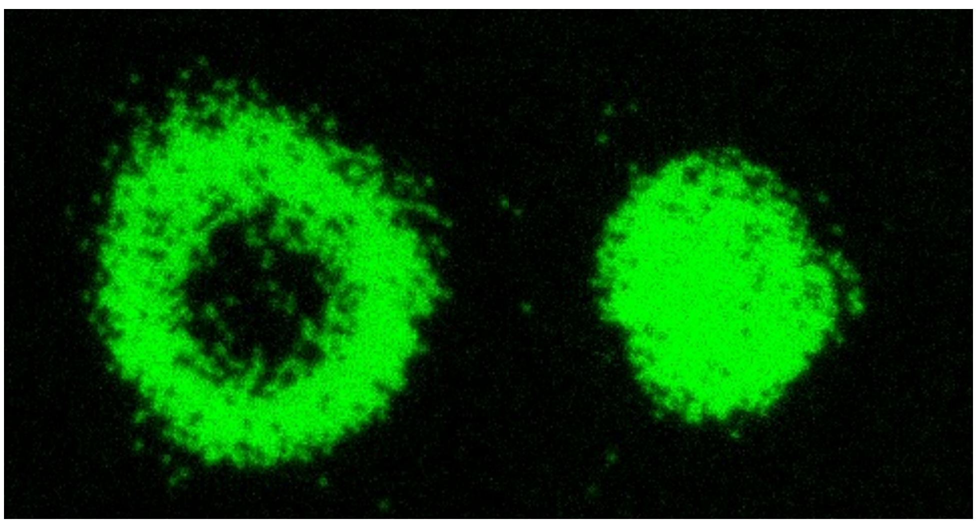


D. Greif et al,
Science **351** 953-957 (2016)

^{40}K



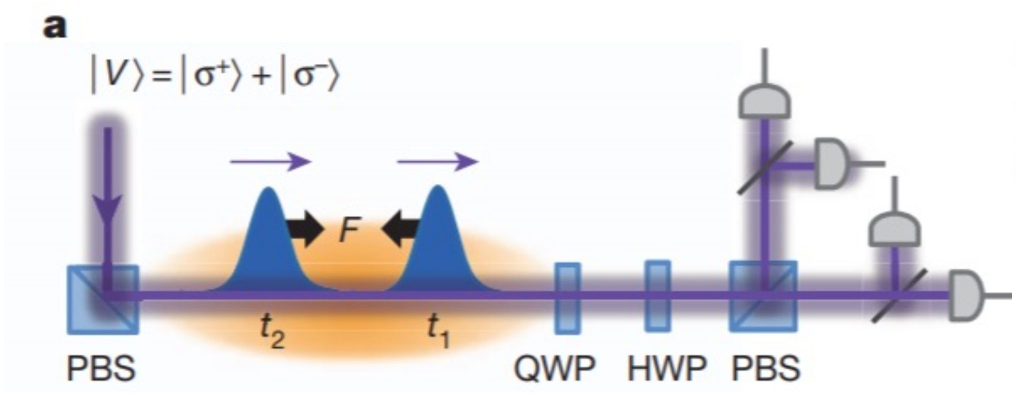
L.W. Cheuk, M.A. Nichols,
K. Lawrence, M. Okan,
H. Zhang, MWZ,
PRL **116**, 235301 (2016)

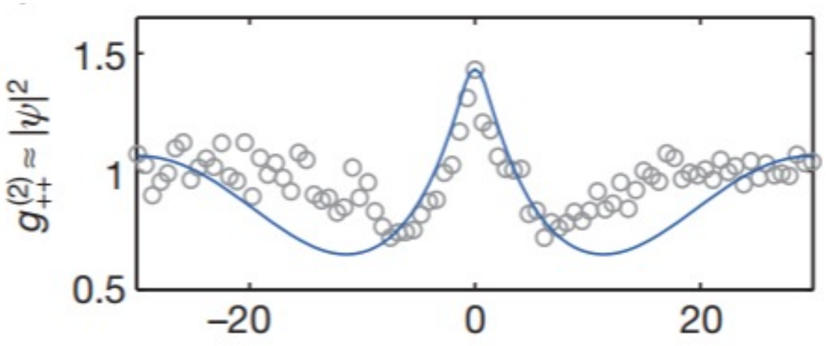


W. Bakr group, Princeton, ultracold.princeton.edu

Interacting Photons

2013 Attractive photons in a non-linear medium (Rydbergs)

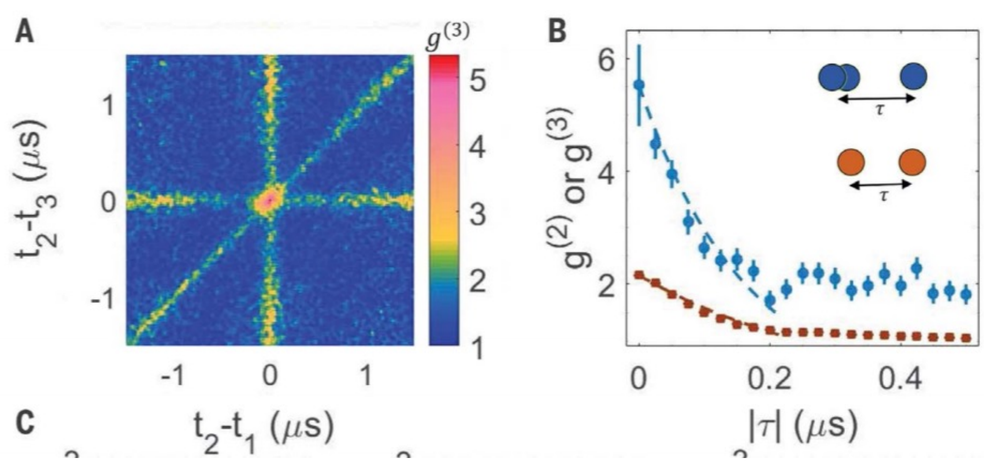




Firstenberg, …, Lukin, Vuletic, Nature 2013

2018 Three-Photon bound states

Liang, … Lukin, Vuletic, Science 2018

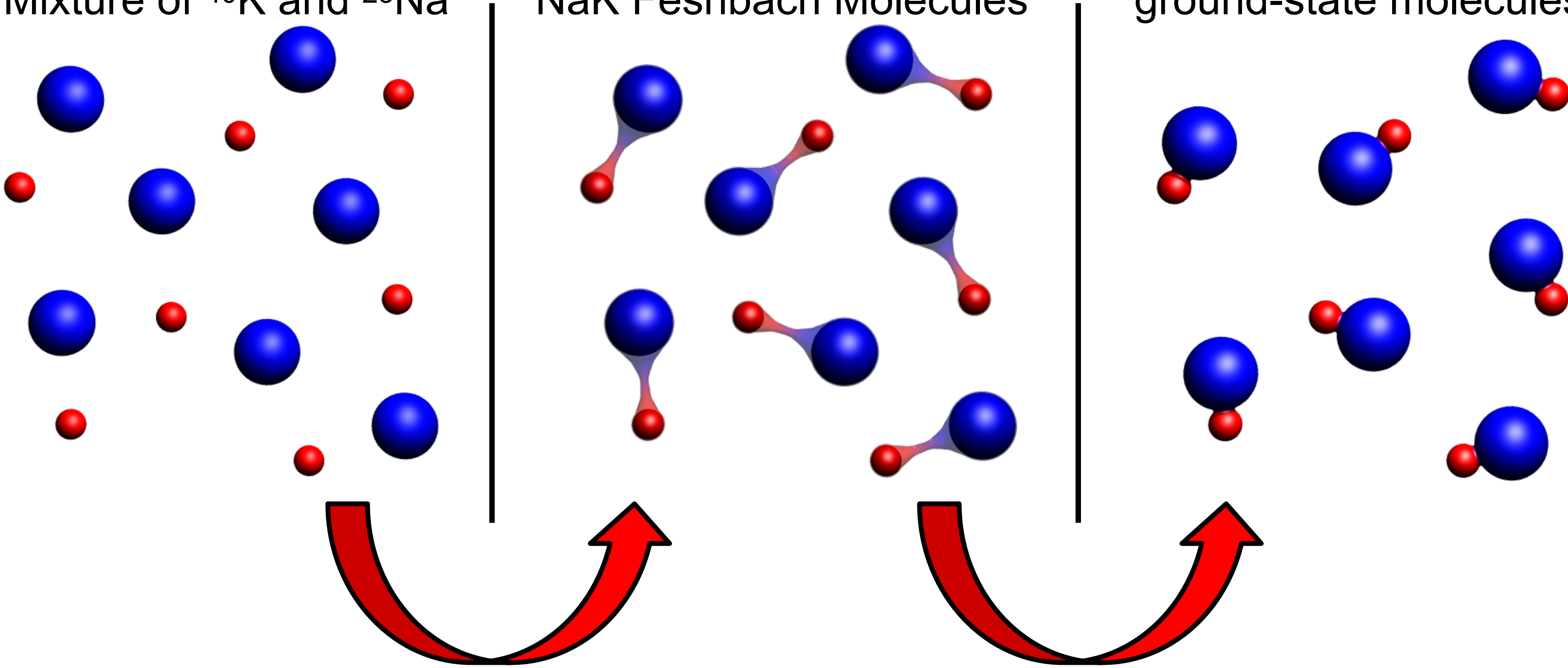


From Ultracold Atoms to Ultracold Molecules

Degenerate Bose-Fermi Mixture of ^{40}K and ^{23}Na

Near-degenerate gas of NaK Feshbach Molecules

Near-degenerate gas of ground-state molecules

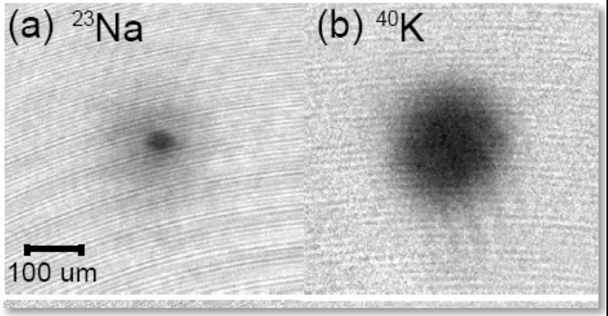


Feshbach Association	Raman Transfer (STIRAP)
Binding energy 100 kHz	→ Binding energy 150 THz ~ 0.6 eV
Internuclear Distance 300 a_0	→ Internuclear Distance 7 a_0
Dipole Moment 5×10^{-11} D	→ Dipole Moment up to 2.7 D

Pioneering work with KRb and Cs_2: K. K. Ni et al., Science 322, 231 (2008)
J.G. Danzl *et al.*, Science 321, 1062 (2008)

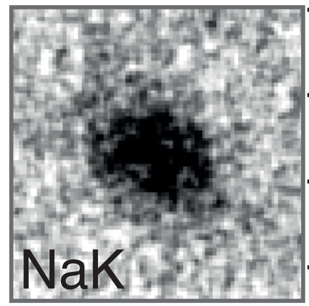
From Ultracold Atoms to Ultracold Molecules

Degenerate Bose-Fermi Mixture of ^{40}K and ^{23}Na



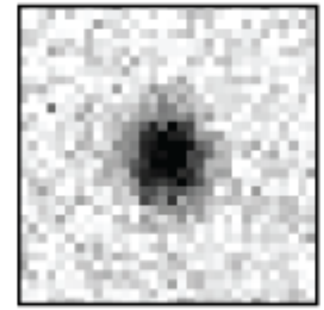
J.W. Park, C.-H. Wu, I. Santiago, T. Tiecke, P. Ahmadi, MWZ, PRA(R) 85, 051602 (2012)

Near-degenerate gas of NaK Feshbach Molecules



C.-H. Wu, J.W. Park, P. Ahmadi, S. Will, MWZ PRL **109**, 085301 (2012)

Near-degenerate gas of ground-state molecules



J.W. Park, S. Will, MWZ, NJP **17**, 075016 (2015)
J.W. Park, S. Will, MWZ, PRL **114**, 205302 (2015)

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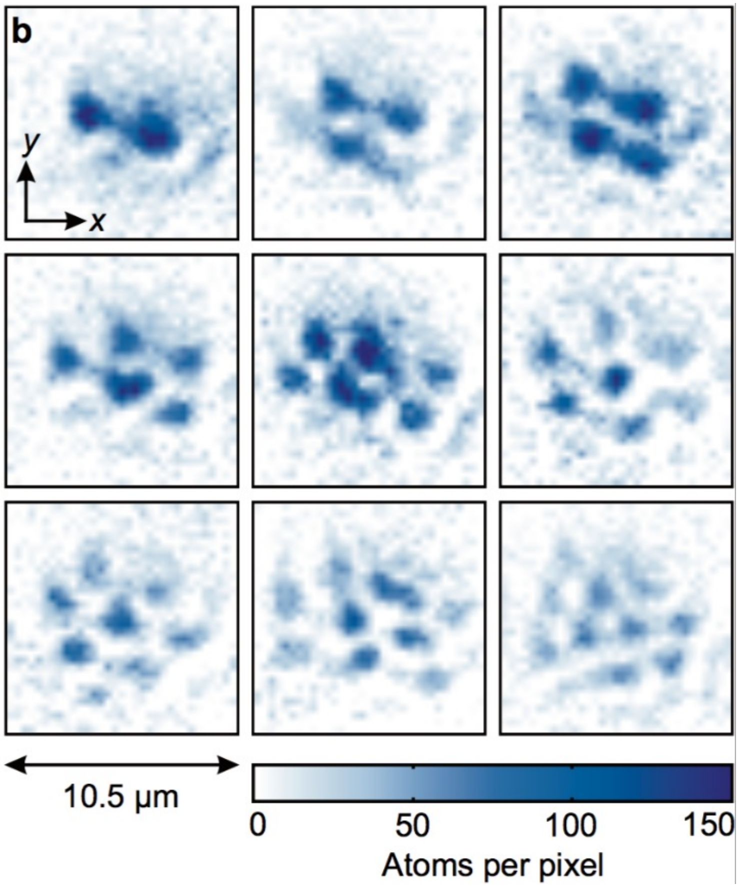
J.G. Danzl *et al.*, Science 321, 1062 (2008)

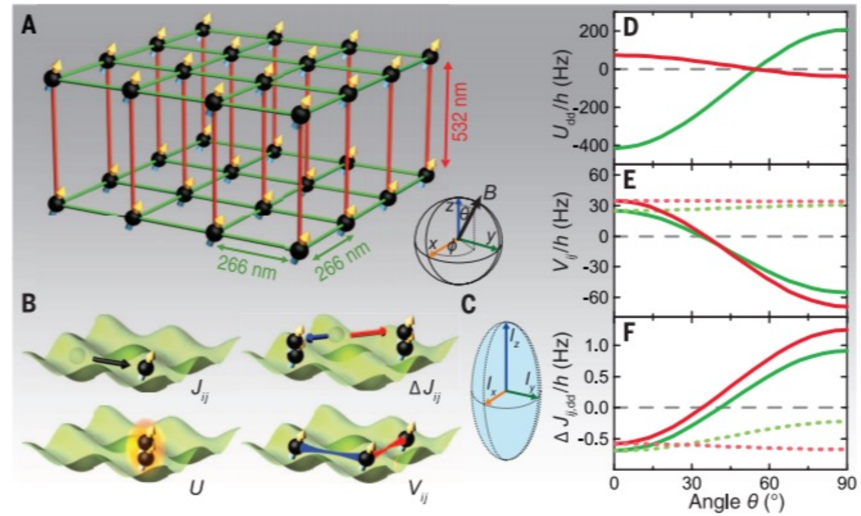
Dipolar Quantum Gases

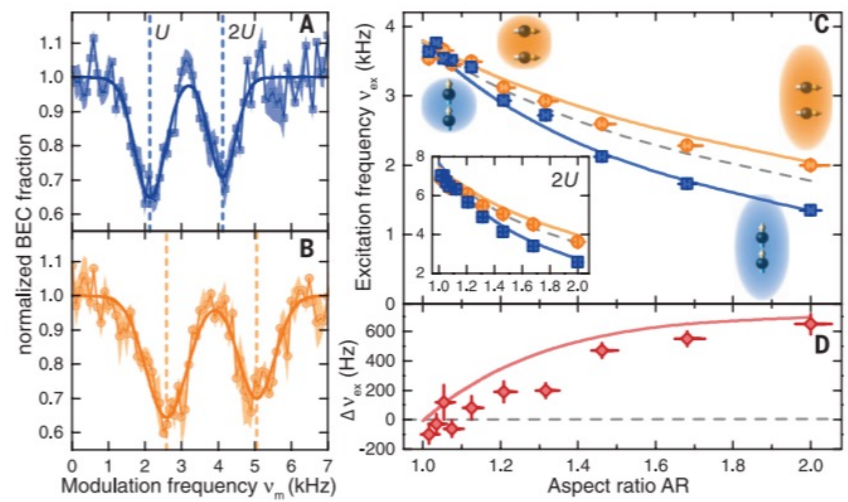
Crystal of dipolar quantum droplets



Pfau group, Stuttgart, Nature 2016

Extended Bose-Hubbard





Ferlaino group, Innsbruck, Science 2016

Dipolar Supersolids

Pfau group, Stuttgart, Nature 2019

The low-energy Goldstone mode in a trapped dipolar supersolid

Mingyang Guo[1,2,4], Fabian Böttcher[1,2,4], Jens Hertkorn[1,4], Jan-Niklas Schmidt[1,2], Matthias Wenzel[1,2], Hans Peter Büchler[2,3], Tim Langen[1,2] & Tilman Pfau[1,2]*

Modugno group, Pisa, Nature 2019

Supersolid symmetry breaking from compressional oscillations in a dipolar quantum gas

L. Tanzi[1,2,3,6], S. M. Roccuzzo[4,5,6], E. Lucioni[1,2,3], F. Famà[1], A. Fioretti[1], C. Gabbanini[1], G. Modugno[1,2,3]*, A. Recati[4,5]* & S. Stringari[4,5]

Ferlaino group, Innsbruck, PRX 2019

Long-Lived and Transient Supersolid Behaviors in Dipolar Quantum Gases

L. Chomaz,[1] D. Petter,[1] P. Ilzhöfer,[2] G. Natale,[1] A. Trautmann,[2] C. Politi,[2] G. Durastante,[1,2] R. M. W. van Bijnen,[2] A. Patscheider,[1] M. Sohmen,[1,2] M. J. Mark,[1,2] and F. Ferlaino[1,2,*]

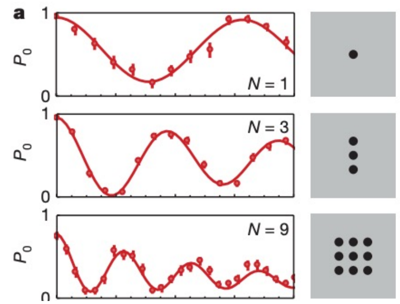
[1]*Institut für Experimentalphysik, Universität Innsbruck, Technikerstraße 25, 6020 Innsbruck, Austria*
[2]*Institut für Quantenoptik und Quanteninformation, Österreichische Akademie der Wissenschaften, Technikerstraße 21a, 6020 Innsbruck, Austria*

Quantum Computation & Simulation

Browaeys group, Paris, Nature 2016

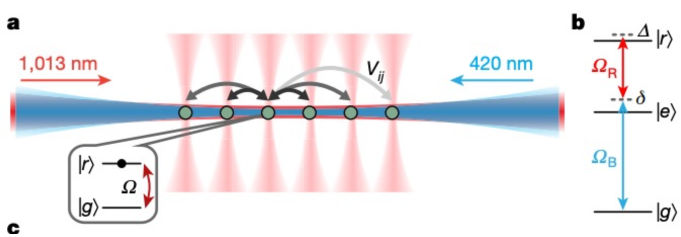
Tunable two-dimensional arrays of single Rydberg atoms for realizing quantum Ising models

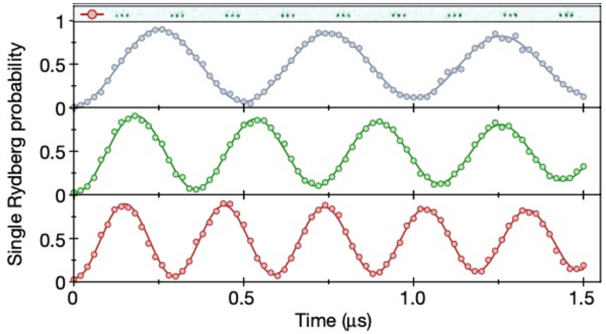
Henning Labuhn[1]*, Daniel Barredo[1]*, Sylvain Ravets[1], Sylvain de Léséleuc[1], Tommaso Macrì[2], Thierry Lahaye[1] & Antoine Browaeys[1]



Probing many-body dynamics on a 51-atom quantum simulator

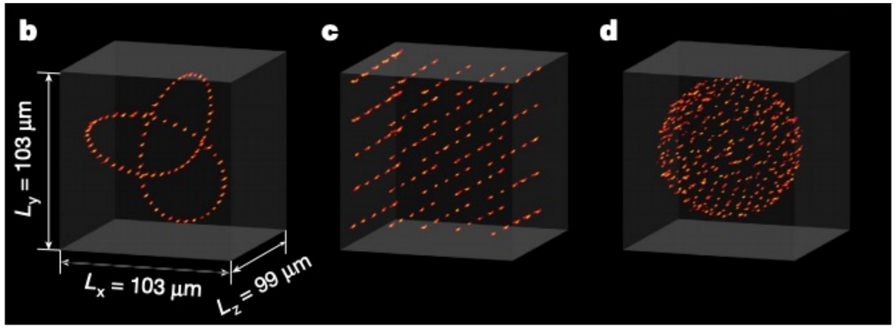
Hannes Bernien[1], Sylvain Schwartz[1,2], Alexander Keesling[1], Harry Levine[1], Ahmed Omran[1], Hannes Pichler[1,3], Soonwon Choi[1], Alexander S. Zibrov[1], Manuel Endres[4], Markus Greiner[1], Vladan Vuletić[2] & Mikhail D. Lukin[1]

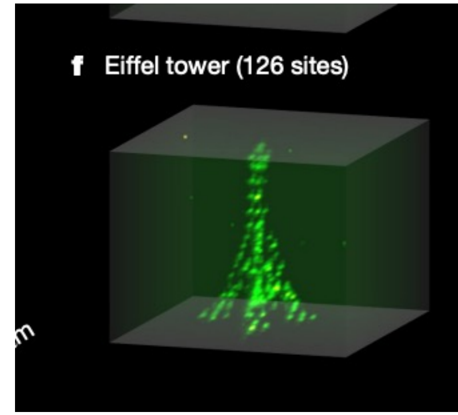




Synthetic three-dimensional atomic structures assembled atom by atom

Daniel Barredo[1,2]*, Vincent Lienhard[1,2], Sylvain de Léséleuc[1,2], Thierry Lahaye[1] & Antoine Browaeys[1]





Generation and manipulation of Schrödinger cat states in Rydberg atom arrays

A. Omran[1]*, H. Levine[1]*, A. Keesling[1], G. Semeghini[1], T. T. Wang[1,2], S. Ebadi[1], H. Bernien[3], A. S. Zibrov[1], H. Pichler[1,4], S. Choi[5], J. Cui[6], M. Rossignolo[7], P. Rembold[6], S. Montangero[8], T. Calarco[6,9], M. Endres[10], M. Greiner[1], V. Vuletić[11], M. D. Lukin[1]†

Quantum Kibble–Zurek mechanism and critical dynamics on a programmable Rydberg simulator

Alexander Keesling[1], Ahmed Omran[1], Harry Levine[1], Hannes Bernien[1], Hannes Pichler[1,2], Soonwon Choi[1], Rhine Samajdar[1], Sylvain Schwartz[3], Pietro Silvi[4,5], Subir Sachdev[1], Peter Zoller[4,5], Manuel Endres[6], Markus Greiner[1], Vladan Vuletić[7] & Mikhail D. Lukin[1]*

21st century AMO:
Many-Body Quantum Physics for

- Discovery of New States of Matter
- Quantum Simulation
- Quantum Computation
- Quantum Sensors
- Precision Measurements
- etc…

Hydrogen:

Balmer formula: $$\frac{1}{\lambda} = R_H \left(\frac{1}{n^2} - \frac{1}{m^2} \right)$$

Rydberg constant: $$R_H = 10973731.568508(65)\ \mathrm{m}^{-1}$$ (Codata 2014)

Note on units: $$1\,\mathrm{eV} \equiv 12000\ \mathrm{K} \equiv 2.4 \cdot 10^{14}\ \mathrm{Hz} \equiv 8066\ \mathrm{cm}^{-1}$$

$$\lambda_{1\,\mathrm{eV}} = 1.23\text{"}45\text{"}10^{-6}\ \mathrm{m} = 1.24\ \mu\mathrm{m}$$

Syllabus

Main Topics

- The Two-State System: Resonance
- Atoms: Some Basics
- Effects of the Nucleus on Atomic Structure
- Atoms in Magnetic Fields
- Atoms in Electric Fields
- Interaction of an Atom with an Electro-Magnetic Field
- Resonance Line Shapes
- Two-Photon Excitation
- Coherence