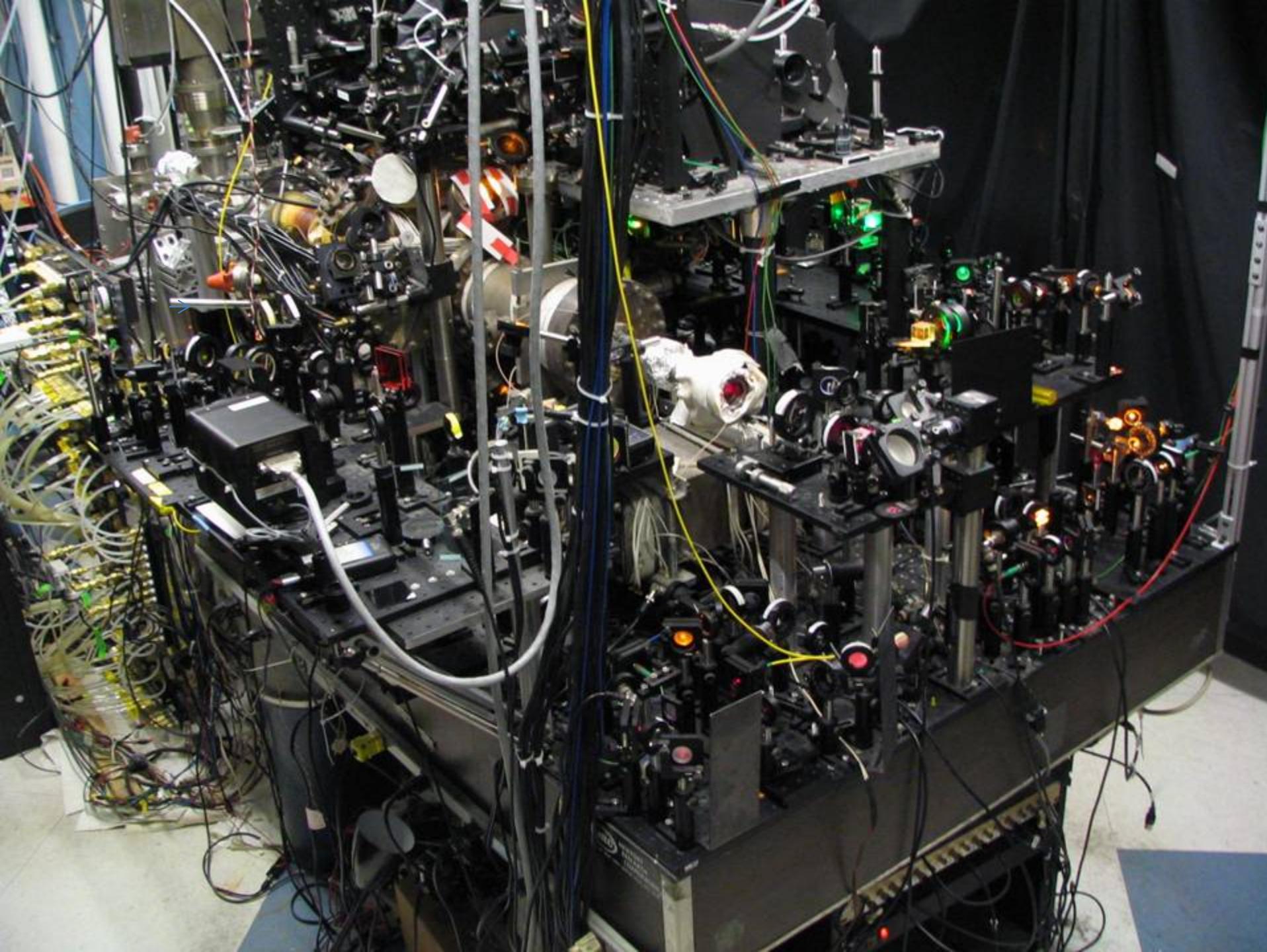


8.422 Atomic Physics II

A Brief History of Atomic Physics



How cold is ultracold?

Atoms move at:

$\sim 1 \text{ mm/s}$

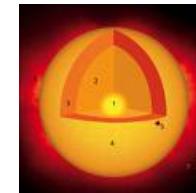
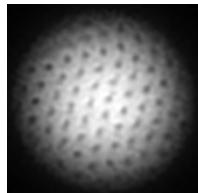
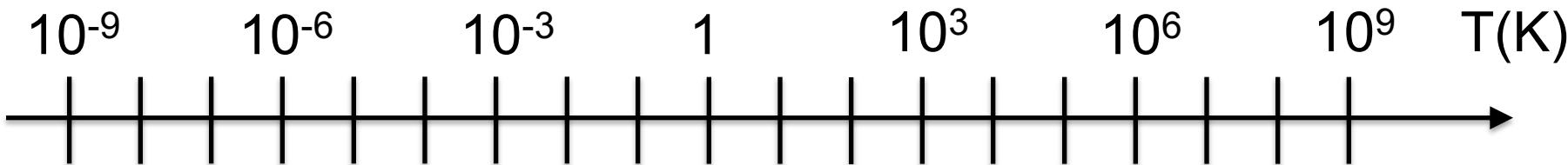


$\sim 100 \text{ m/s}$



$\sim 10^6 \text{ m/s}$

Boston – Paris
in 10 seconds



Ultracold atom
experiments

Outer
space

Your
living
room

Center
of the
sun

Supernova
explosion

Particles behave as waves

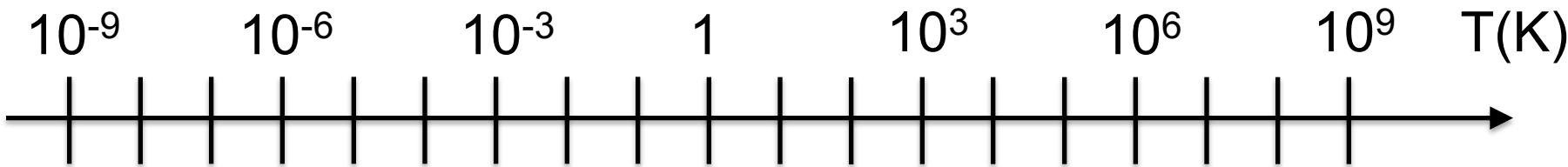


*Louis
de Broglie*

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

Mass

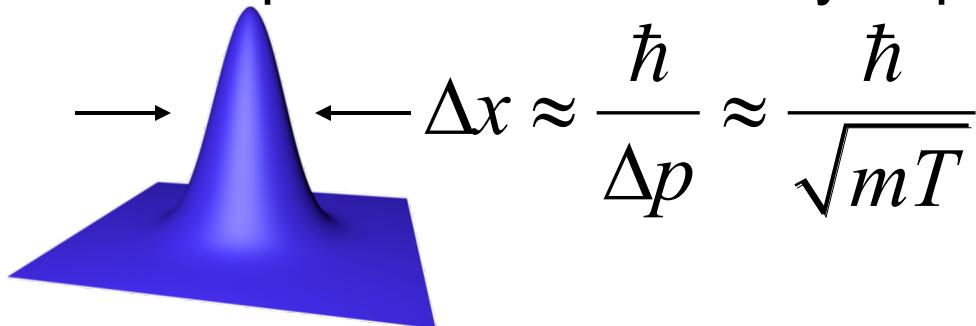
Planck's constant
Velocity



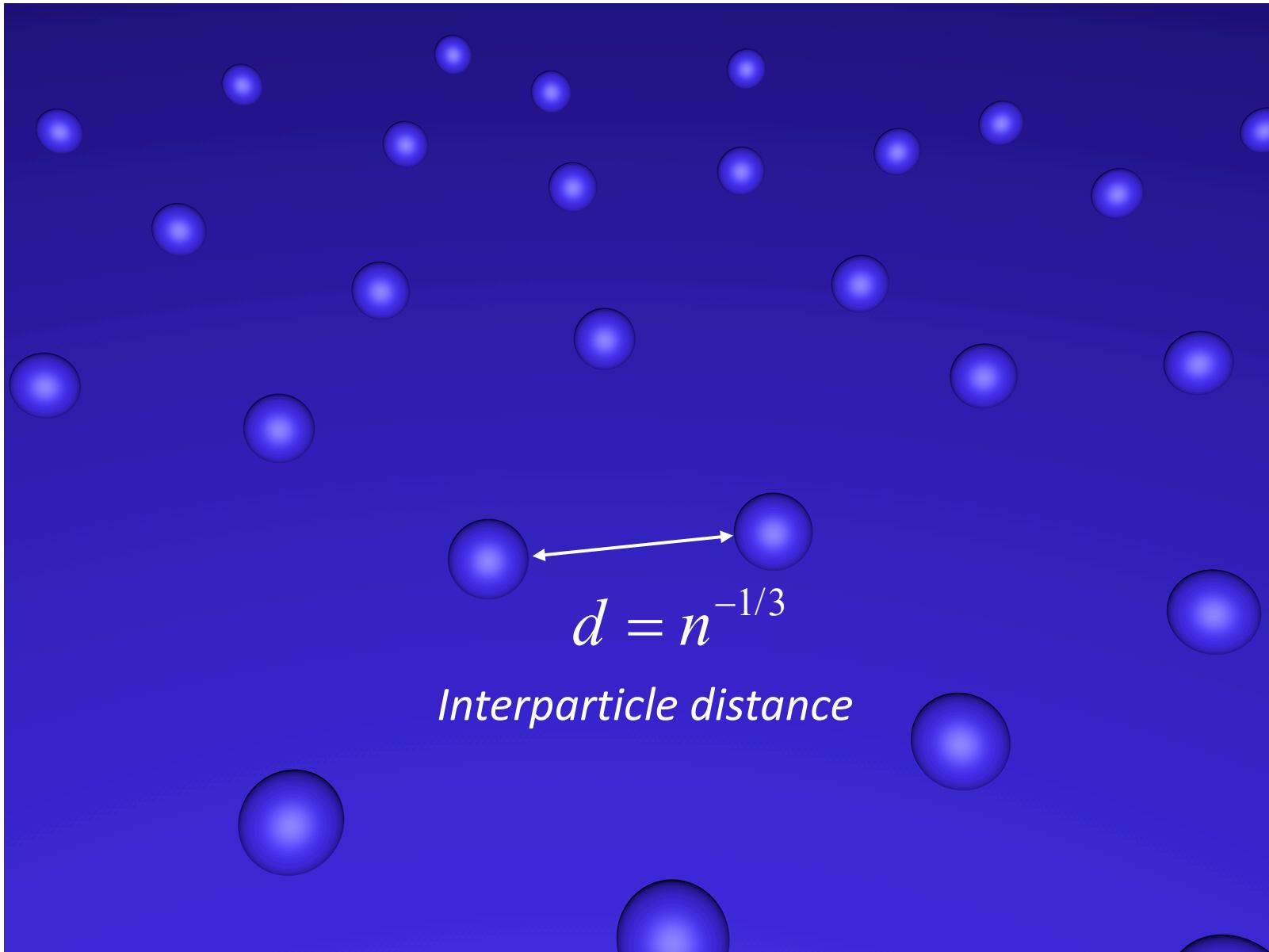
*Werner
Heisenberg*

Temperature = Uncertainty of velocity²

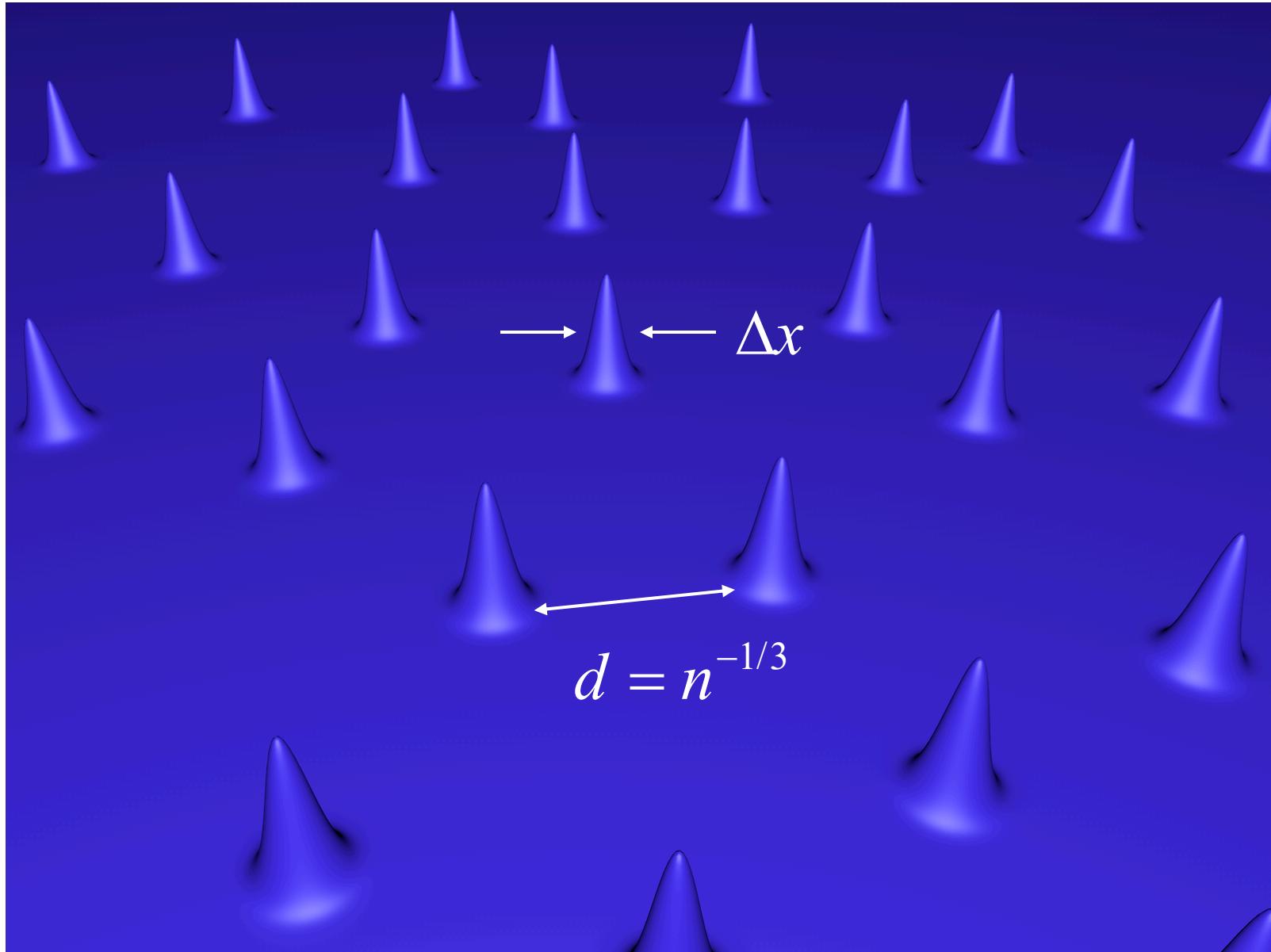
Size of a wave packet = Uncertainty of position



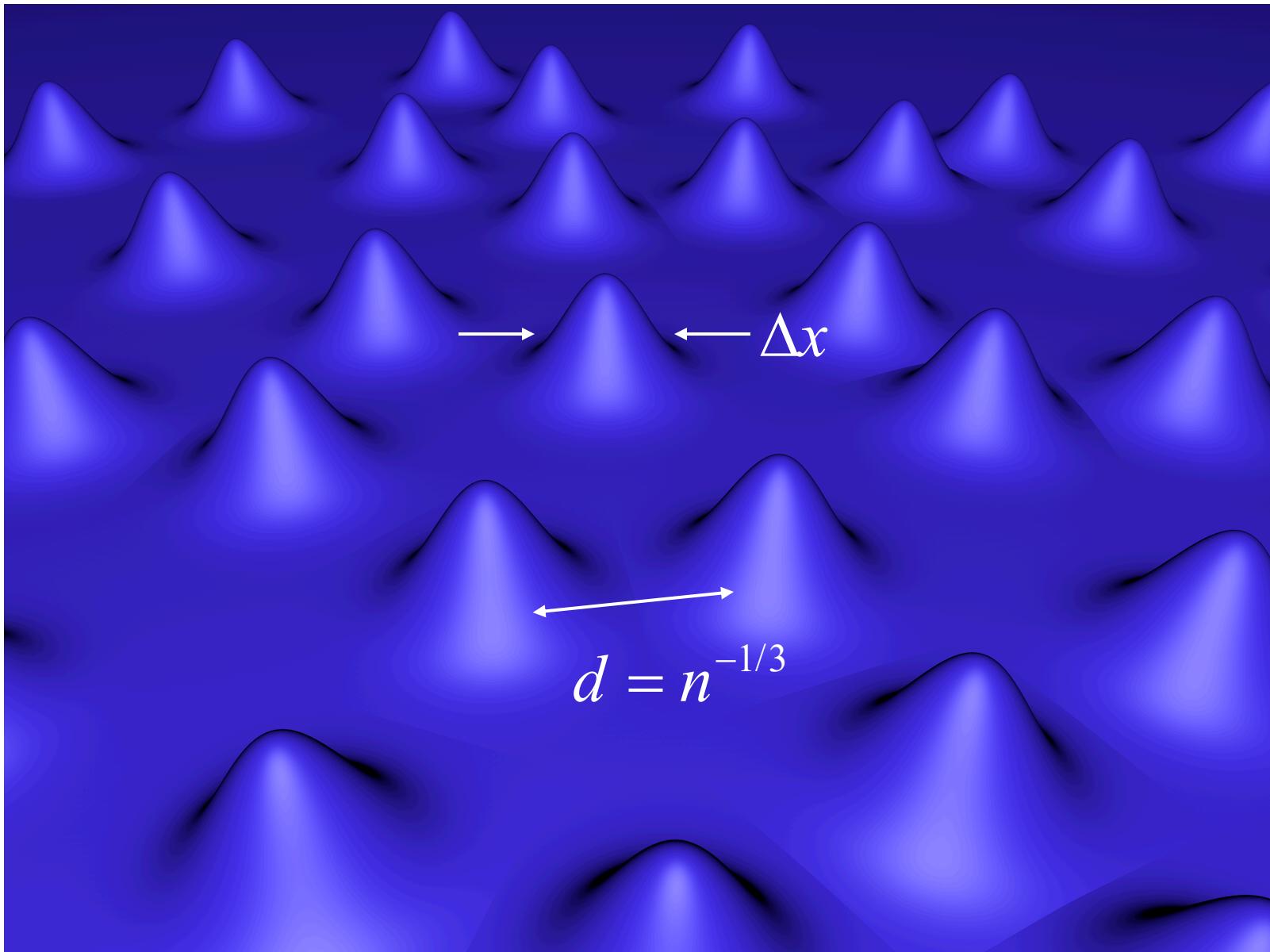
Particles...



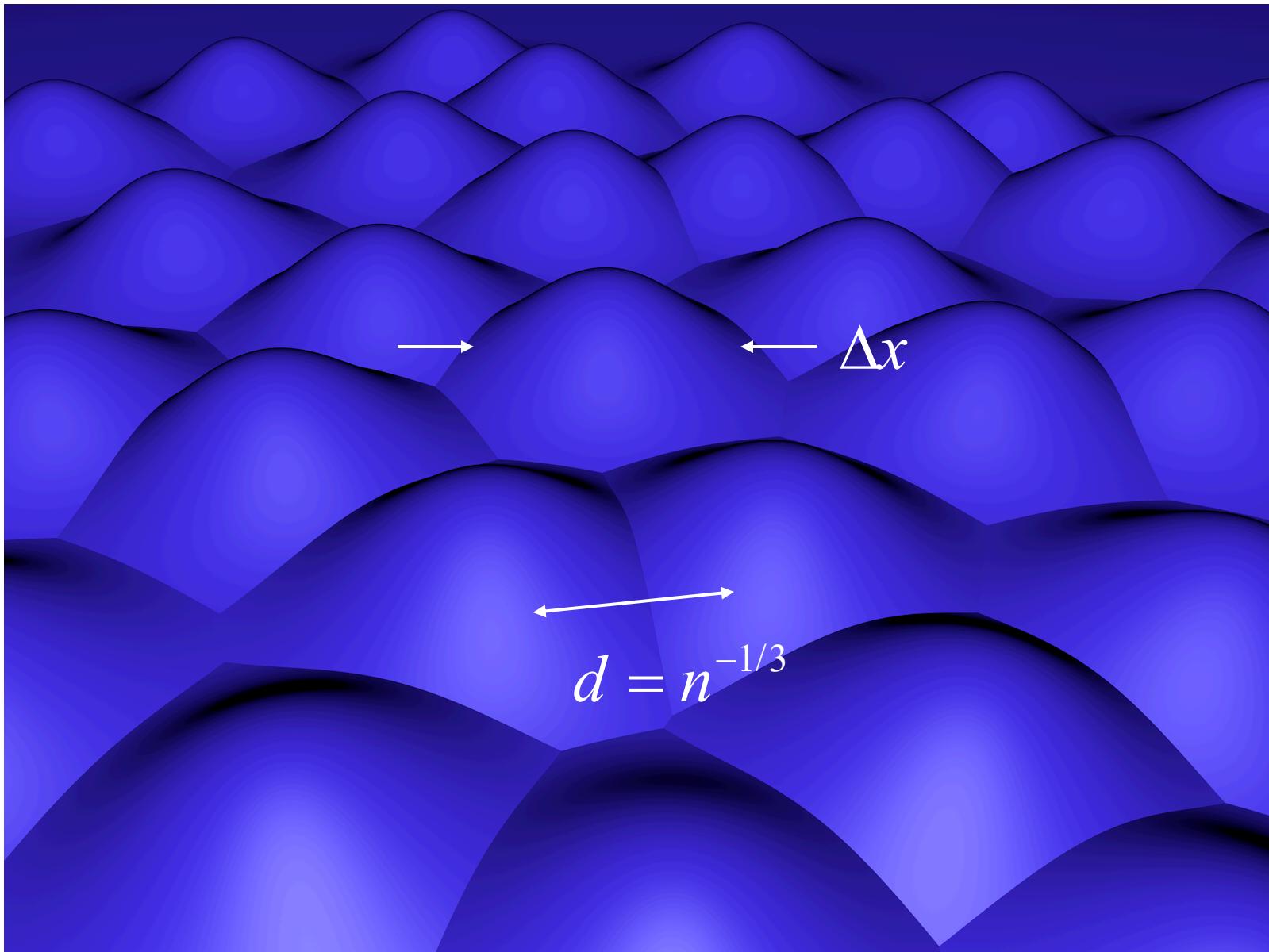
...behave as waves



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

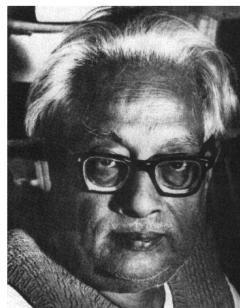
Bosons (sociable):

Integer Spin

Can share quantum states

At low temperatures:

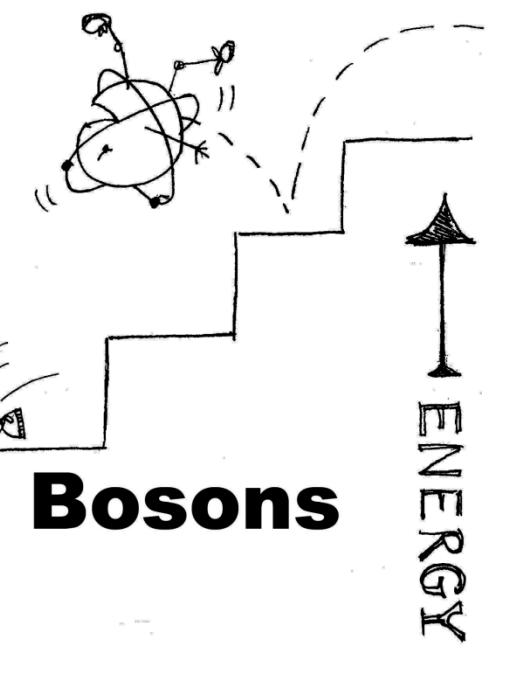
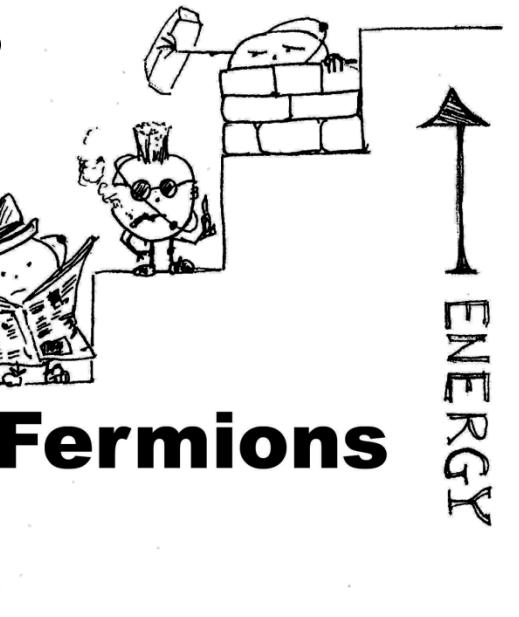
Bose-Einstein condensation



Bose 1924

Einstein 1924/25

Fermions



Bosons

Bosons



N bosons sharing one and the same macroscopic matter wave

(Artist's conception)

Fermions

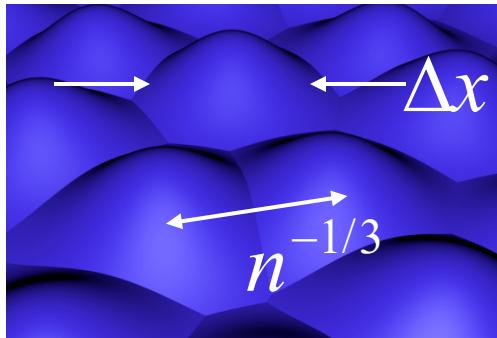


N fermions avoiding each other

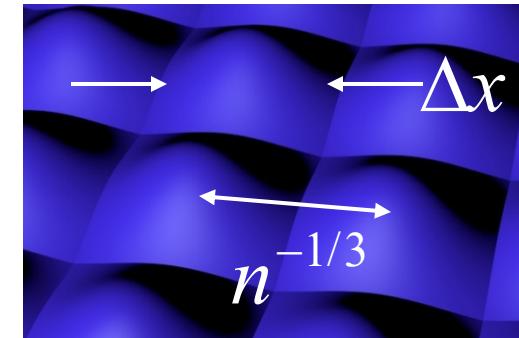
(Artist's conception)

Condition for quantum degeneracy

Position uncertainty \sim Interparticle spacing

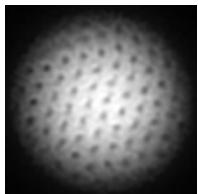
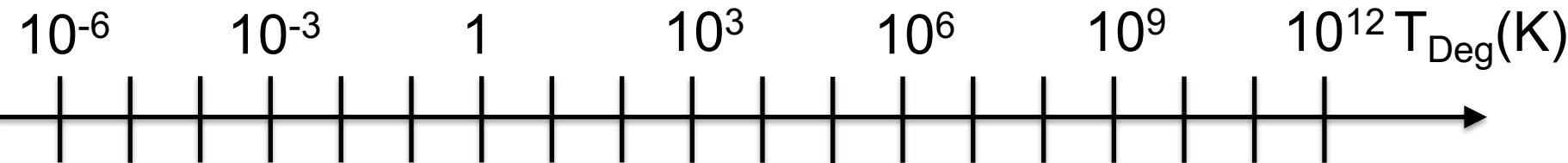


$$\Delta x = \frac{\hbar}{\Delta p} \approx n^{-1/3}$$



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

Fermi energy



Ultracold
atomic gases



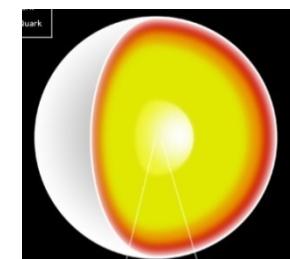
Liquid Helium



Metals



White dwarf



Neutron star

The cooling methods

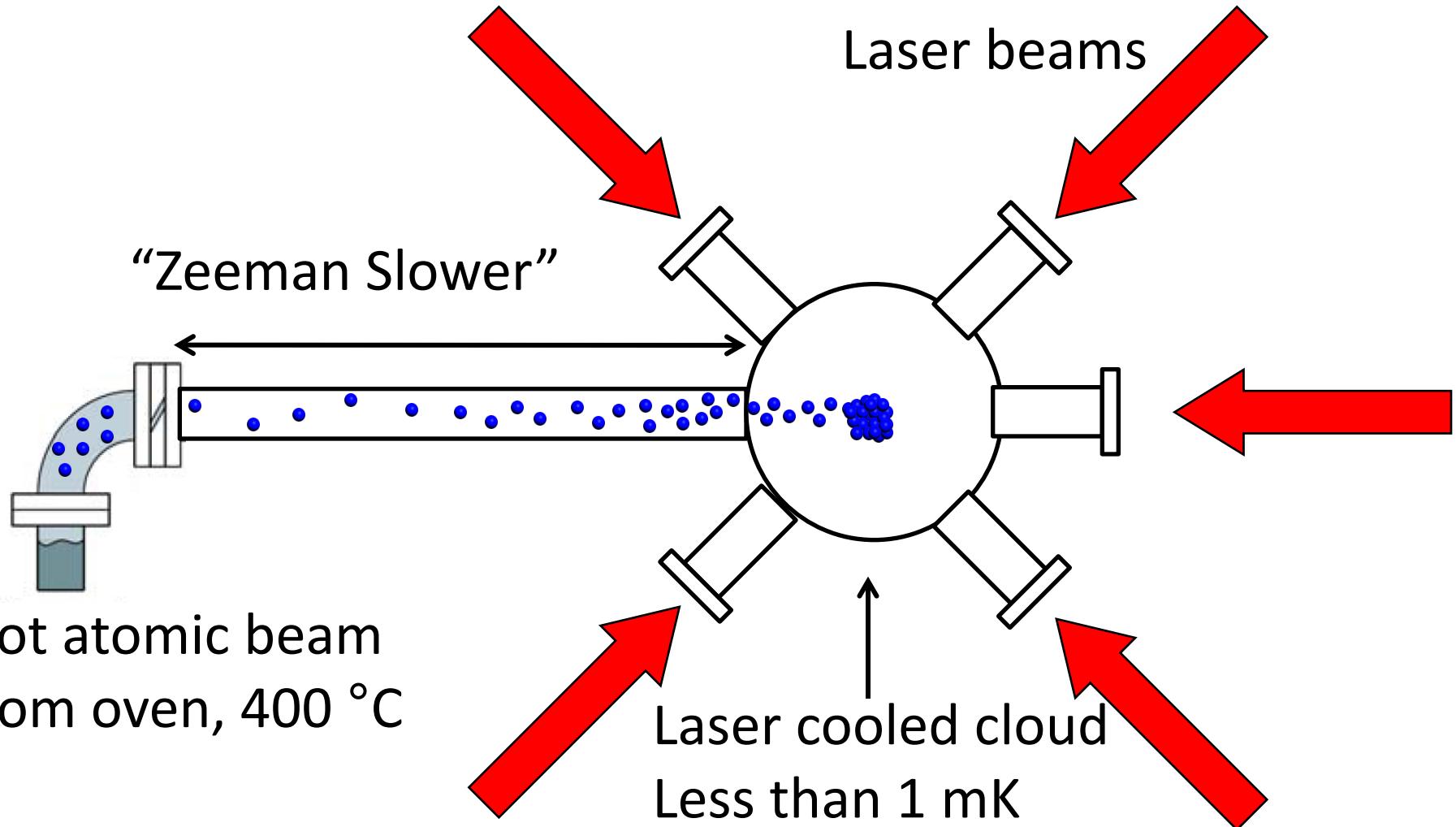
- Laser Cooling $\rightarrow \sim 1 \text{ mK}$



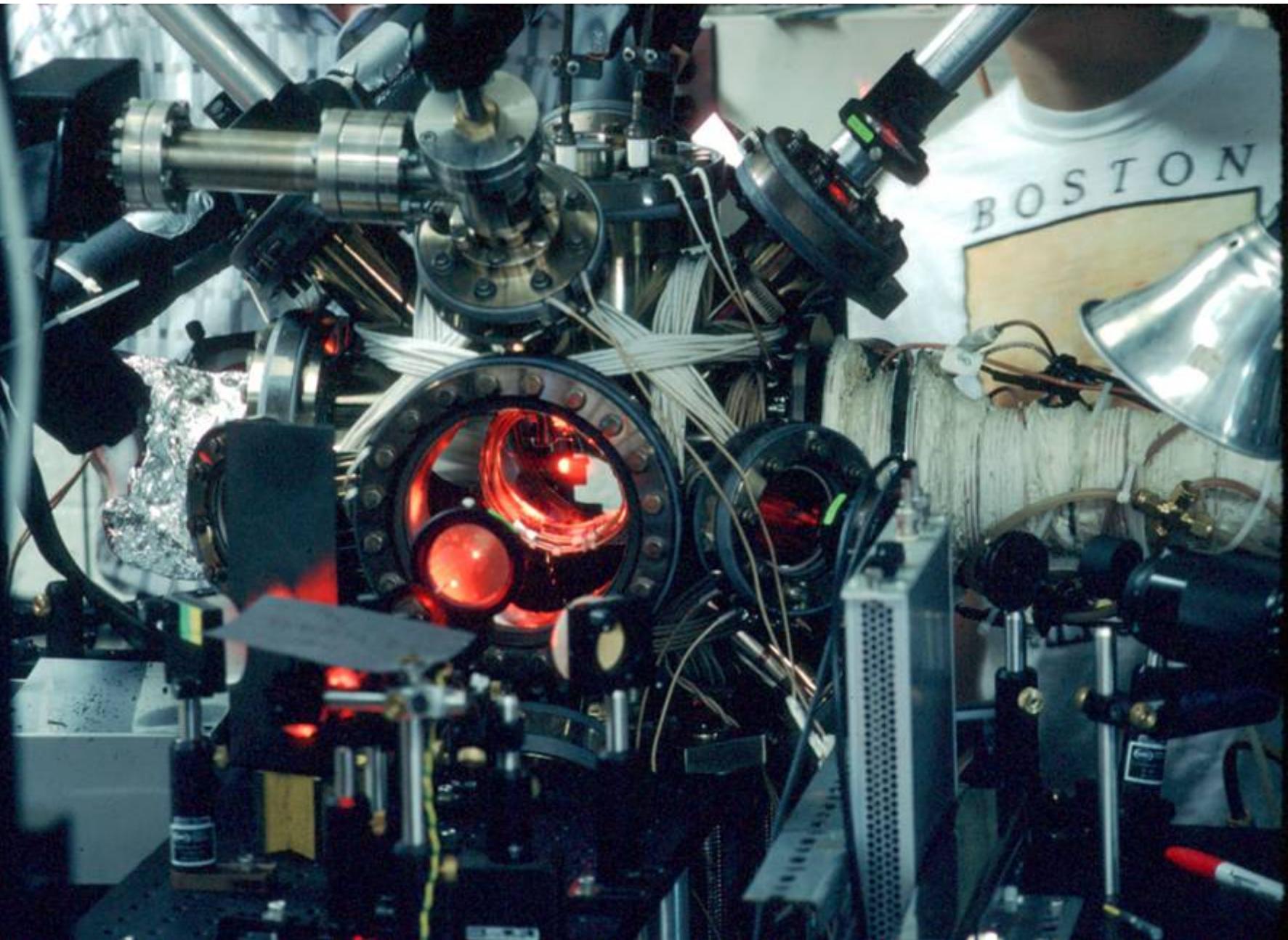
- Evaporative Cooling $\rightarrow \sim 10 \text{ nK}$

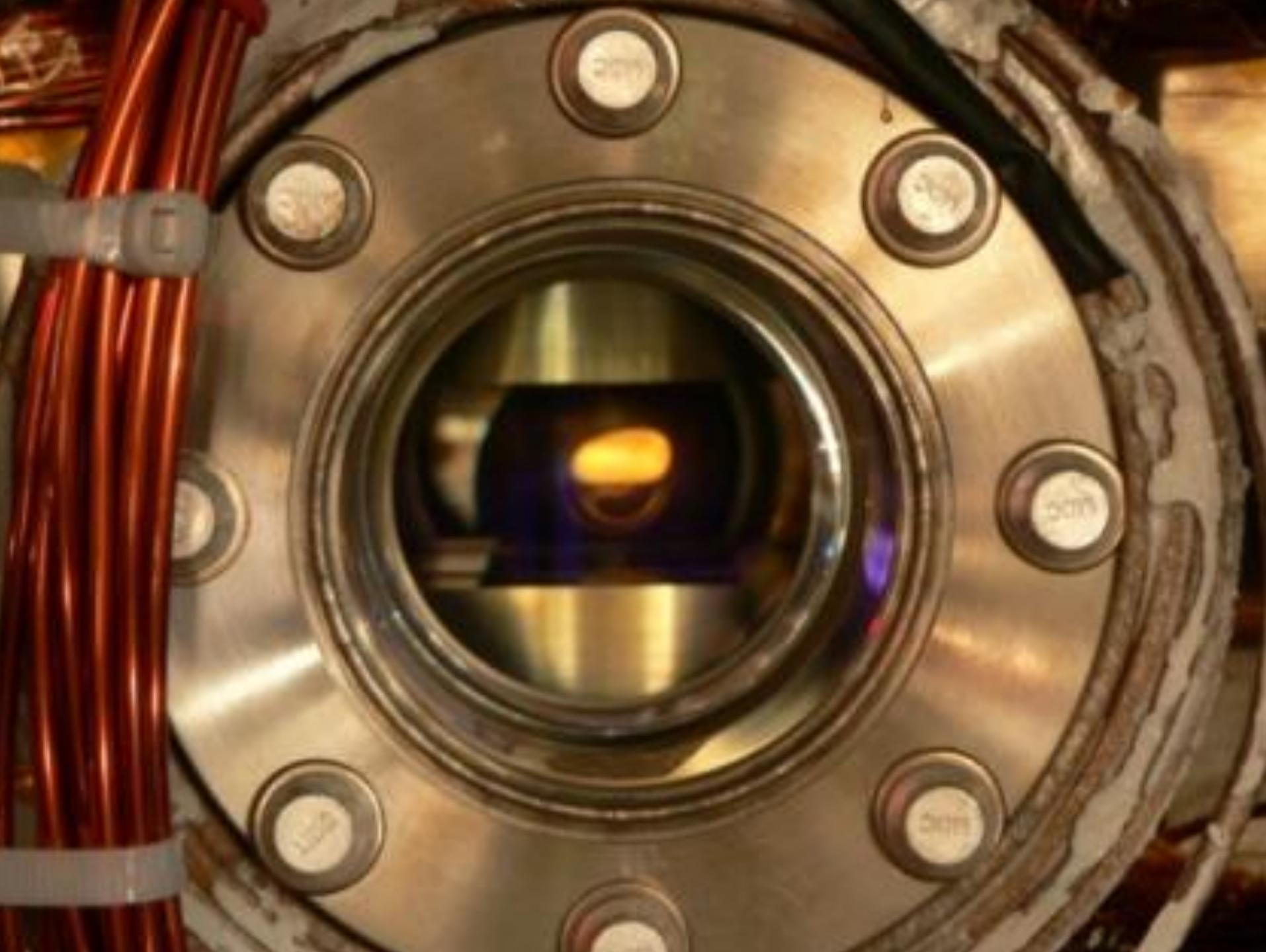


Laser Cooling



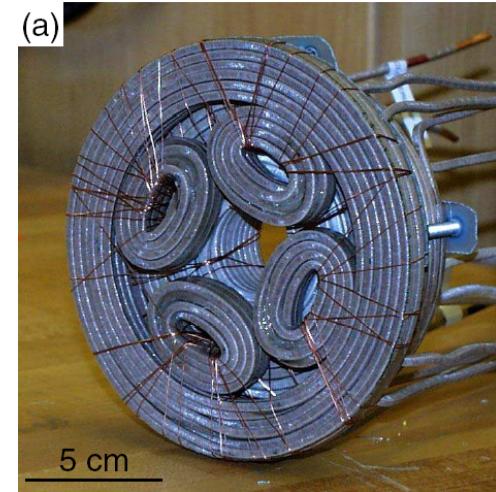
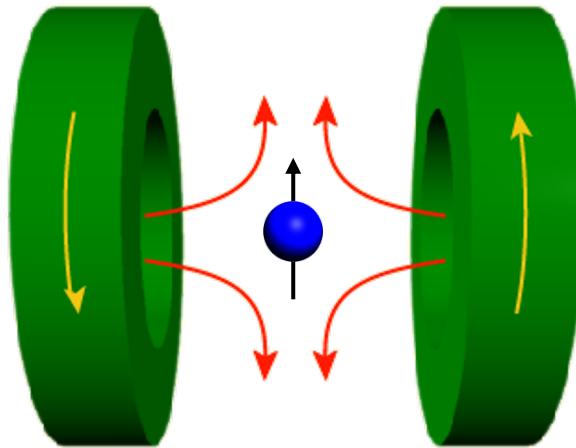
Chu, Cohen-Tannoudji, Phillips, Pritchard, Ashkin, Lethokov, Hänsch,
Schawlow, Wineland ...



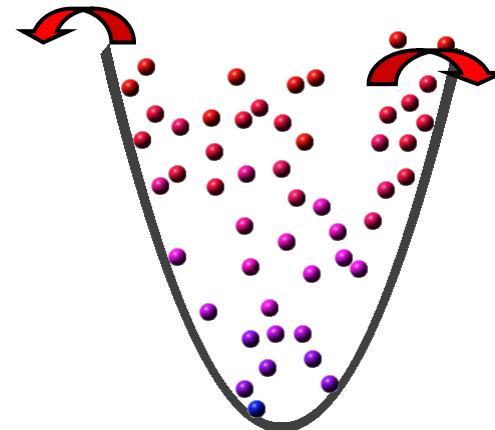


Techniques

Magnetic Trapping



Evaporative Cooling



Evaporative Cooling



First invented and demonstrated for Spin-polarized hydrogen @ MIT Hydrogen group Kleppner, Greytak
Idea: Harold Hess, 1986

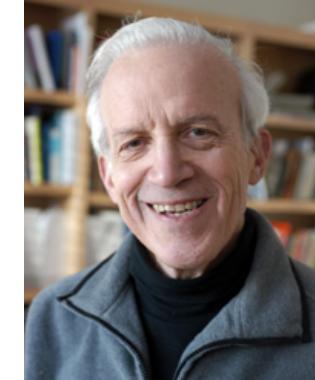
1st Evaporation of hydrogen: 1988

RF-evaporation: Pritchard, 1989

Alkalies: Ketterle and Cornell, Wieman 1995



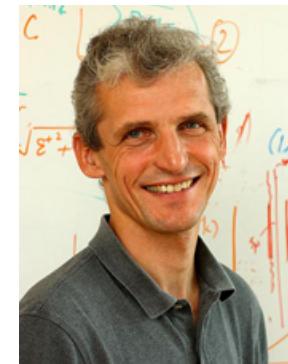
Tom Greytak



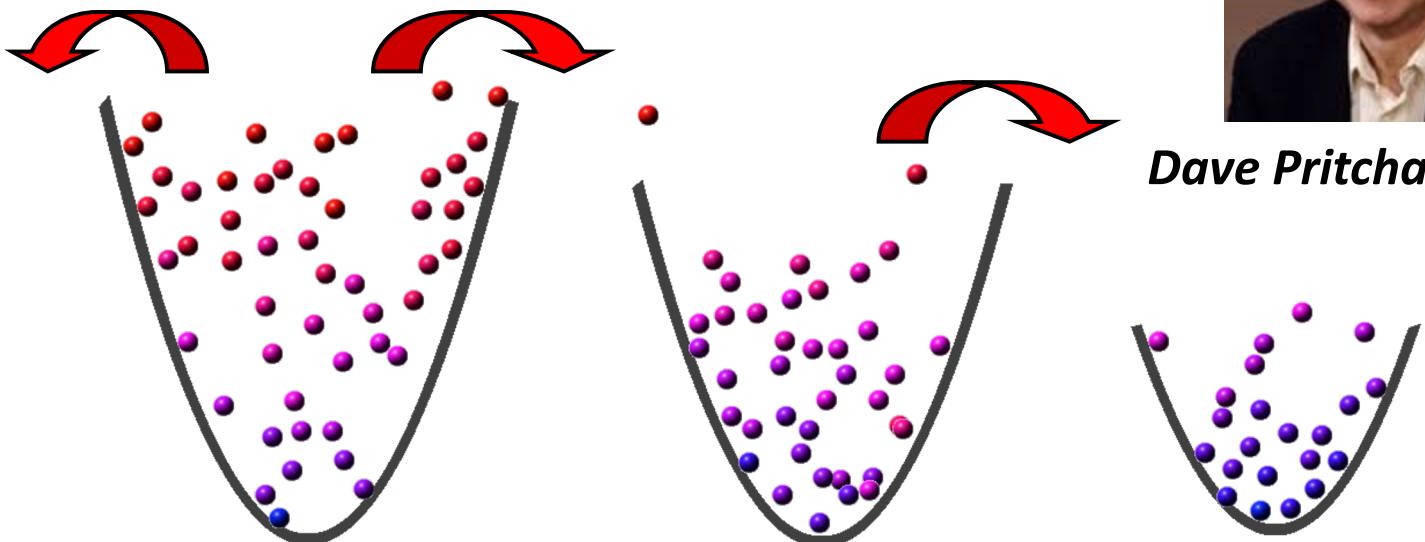
Dan Kleppner



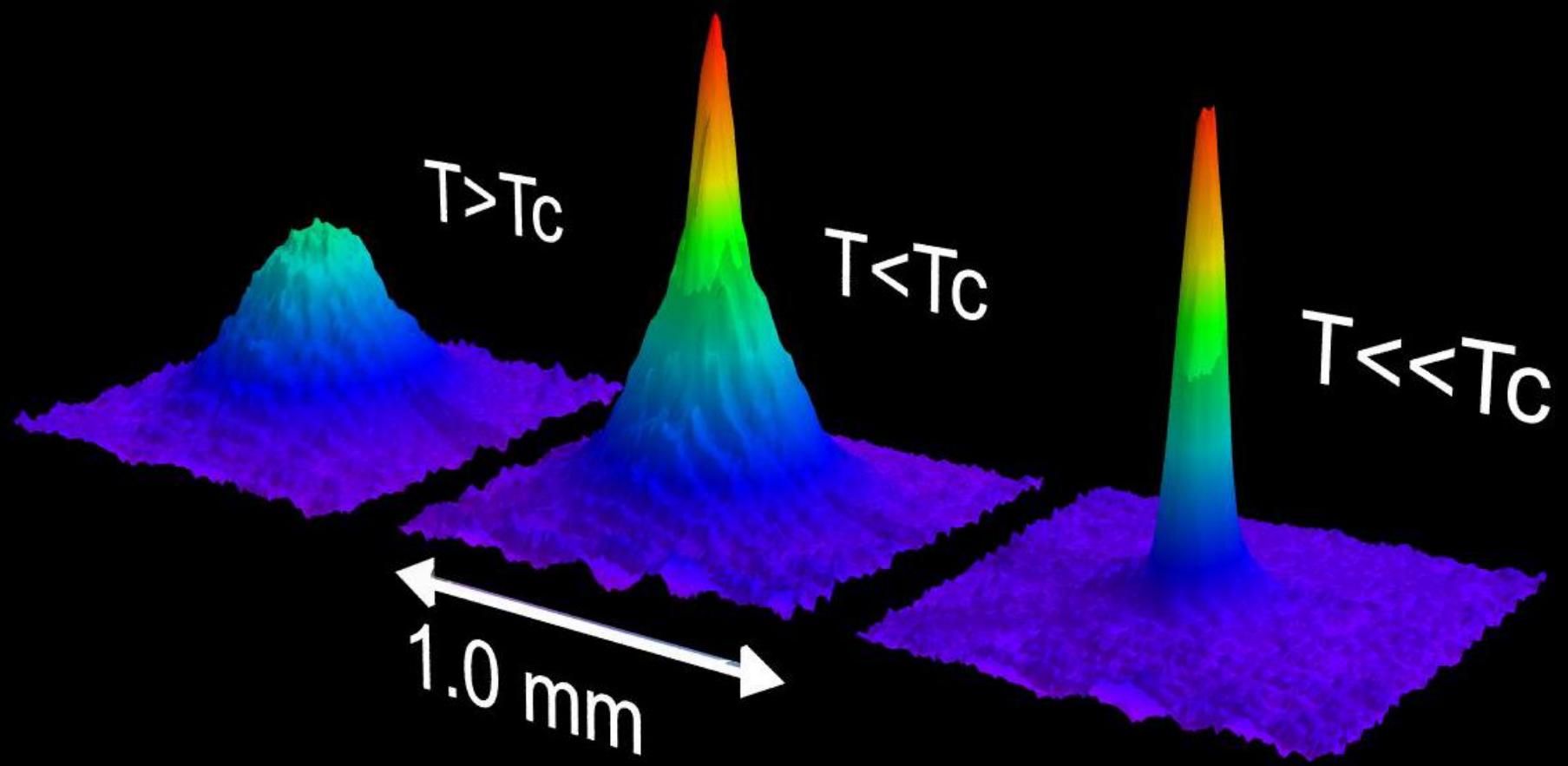
Dave Pritchard



Wolfgang Ketterle



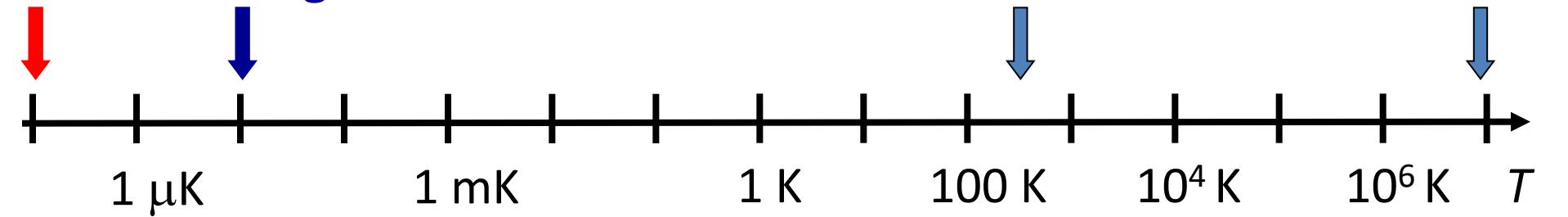
BEC @ MIT, 1995 (Sodium)



The cooling methods on the temperature scale

Evaporative

Cooling Laser
to BEC cooling



Nobel Prize 2001

E. Cornell, W. Ketterle, C. Wieman



Nobel Prize 1997

S. Chu, C. Cohen-Tannoudji, W. Phillips

0 s

30 s in the life of an atom cooler

30 s time →

Loading	Optical	Optical	Magnetic Trapping	Evaporative Cooling to BEC
Magneto-	Molasses	Pumping	Trapping of ions:	NP 2001
Optical	NP 1997	NP 1966	NP 1989	E. Cornell, C. Wieman,
Trap	S. Chu	A. Kastler	W. Paul	W. Ketterle
NP 1997	"Sisyphus"	+	H. Dehmelt	using RF magnetic resonance
From an	Cooling"	Hyperfine		NP 1944
Atomic Beam	C. Cohen-	Purification		I. I. Rabi
NP 1943	Tannoudji	via Rabi flop		NP 1952
O. Stern		NP 1944		Bloch & Purcell
via a Zeeman		I.I. Rabi		
Slower		NP		
NP 1901				
Lorenz & Zeeman				
NP 1997				
B. Phillips				
Using lasers				
NP 1964				
Townes,				
Basov&Prokhorov				
& laser spectroscopy				
NP 1981				
Bloembergen, Schawlow				

Examples of experiments with BEC / Cold Gases

• • • →

30 s

35 s

Clock Shift measurements	Feshbach Association	Raman Sideband
Via Ramsey Sequence	& STIRAP to form	Cooling (e.g. for
NP 1989	ground-state molecules	single-site
N. Ramsey		Imaging)
Cavity QED (with BEC)	Using Frequency combs	NP 2012
NP 2012	NP 2005	D. Wineland
S. Haroche	T. Hänsch, J. Hall	

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. fails to describe a thermal radiation field

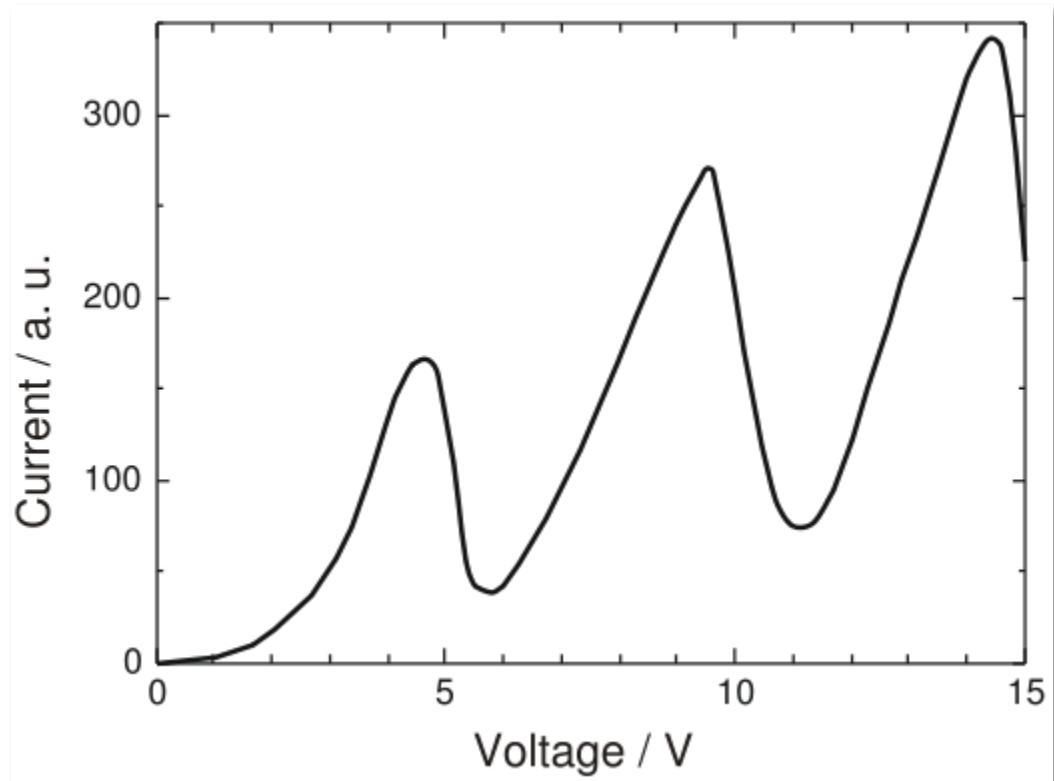
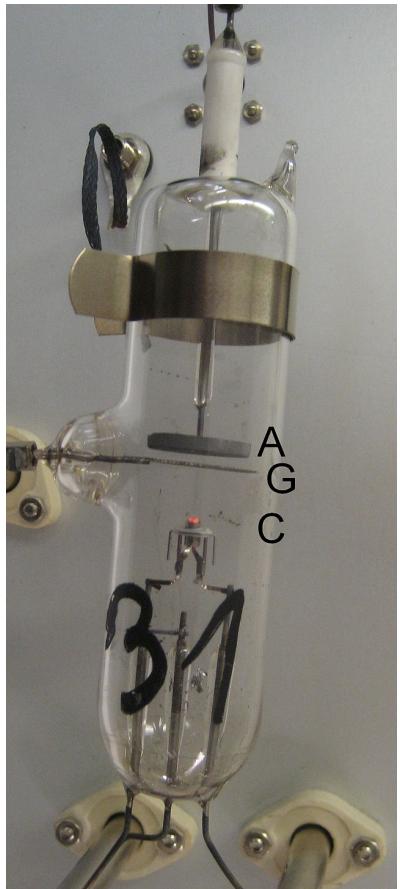
→ Theories of Relativity, Gravitation by Einstein

→ Quantum Mechanics: Planck, Einstein, Bohr, de Broglie, Heisenberg, Schroedinger, Dirac, Pauli, Born, ...

Franck-Hertz experiment 1914

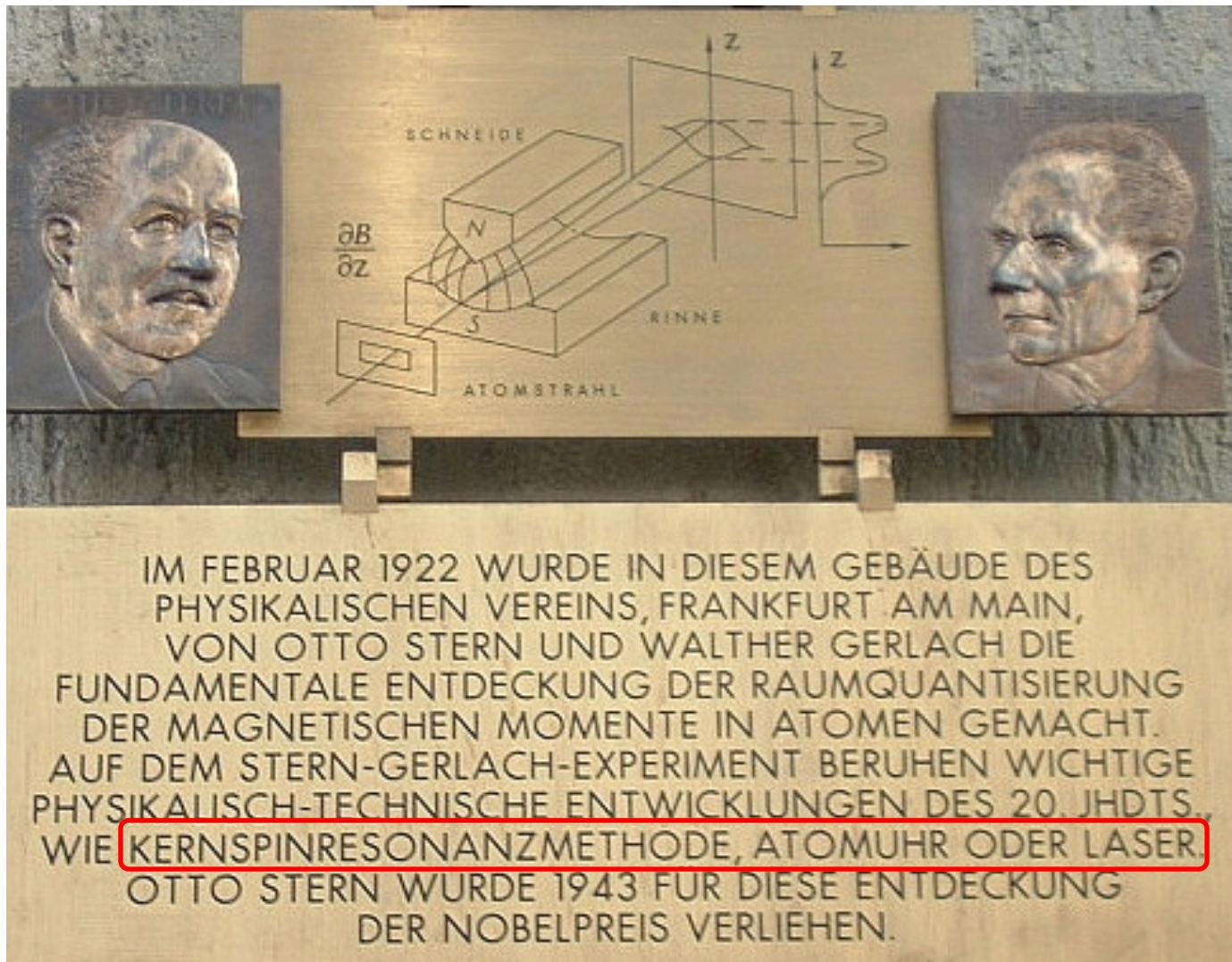
Quantization of energy levels

+ 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)
ν_H	1421.3 ± 0.2 Mc	1416.90 ± 0.54 Mc
ν_D	327.37 ± 0.03 Mc	326.53 ± 0.16 Mc
ν_H/ν_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!

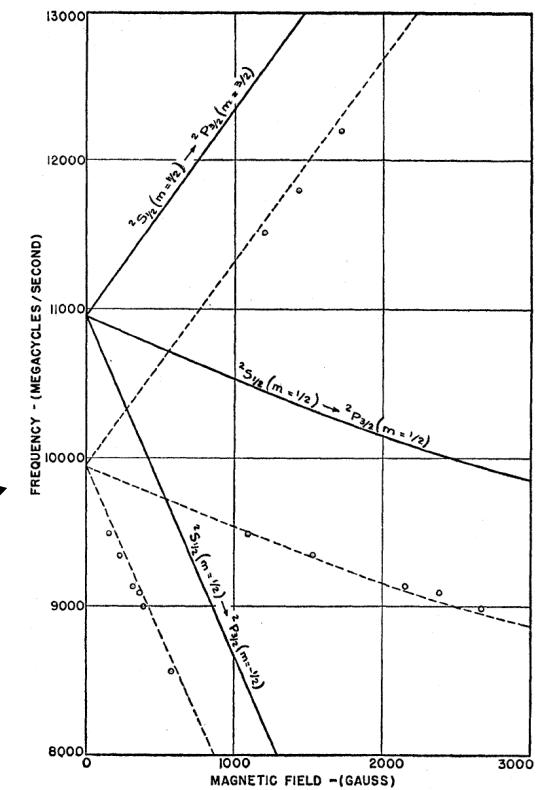
TABLE X. Observed ratios of atomic g values and the corresponding values of δ_S .

Phys. Rev. 74, 250
(1948)

	Experimental ratio	δ_S
$g_J(^2P_{3/2}\text{Ga})/g_J(^2P_1\text{Ga}) = 2(1.00172 \pm 0.00006)$	0.00114 ± 0.00004	
$g_J(^2S_{1/2}\text{Na})/g_J(^2P_1\text{Ga}) = 3(1.00242 \pm 0.00006)$	0.00121 ± 0.00003	
$g_J(^2S_{1/2}\text{Na})/g_J(^2P_{1/2}\text{In}) = 3(1.00243 \pm 0.00010)$	0.00121 ± 0.00005	

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! →

- Dirac theory fails!
- Q E D Schwinger, Feynman, Tomonaga
(NP 1965)



Phys. Rev. 71, 914 (1947)

Magnetic Resonance

I. I. Rabi 1933

NP 1944

Magnetic Resonance Technique

→ measure magnetic moments by measuring a frequency

→ Observe atomic and molecular systems in isolation

→ CONTROL over internal states

→ Wealth of information on atomic + molecular structure

+ on nuclear properties (deuteron has quadrupole moment!)

N. Ramsey 1950

NP 1989

Separated Oscillatory Field Technique

→ Opened way to study internal molecular interactions in H₂

→ 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 crystal)
A. Javan & Bennett 1960 CW Laser (He-Ne)

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

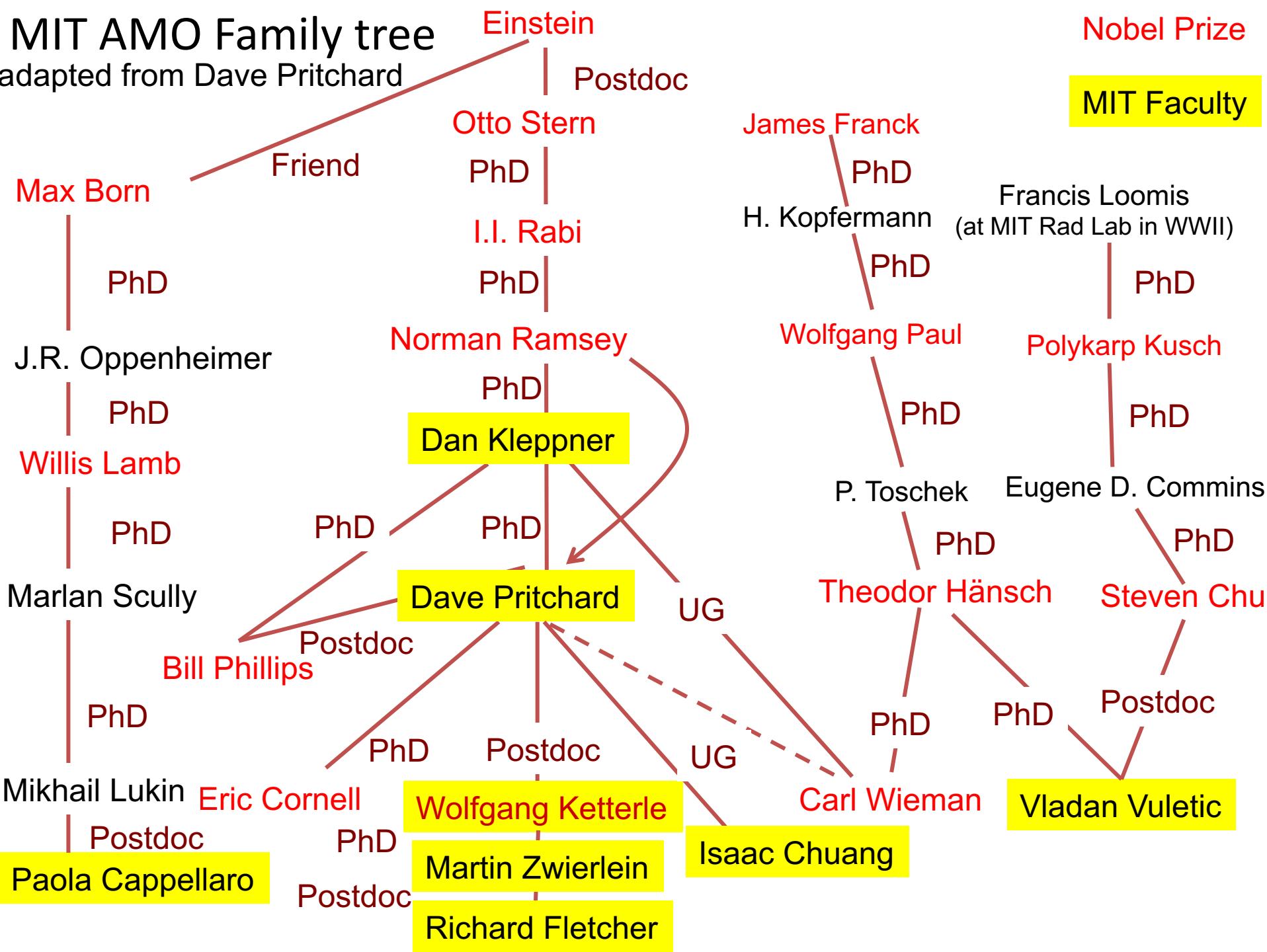
W. Paul 1953 Ion trap
NP 1989 → CONTROL over external motional degrees
→ Mass spectrometer

Nobel Prizes in Atomic/Photonic Control

Spatial

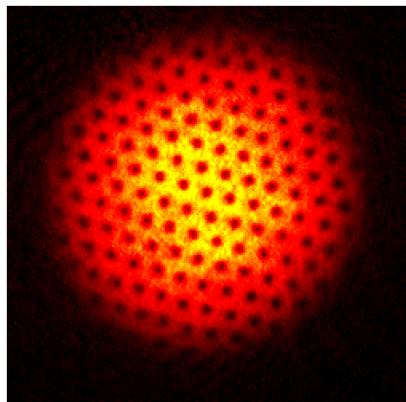
Internal

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	



AMO in Modern Times

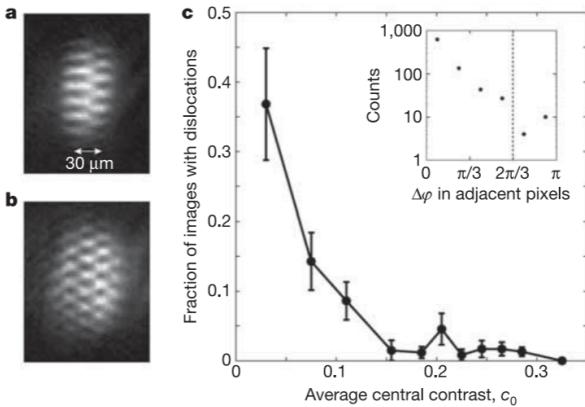
1995-today



Studies of BECs

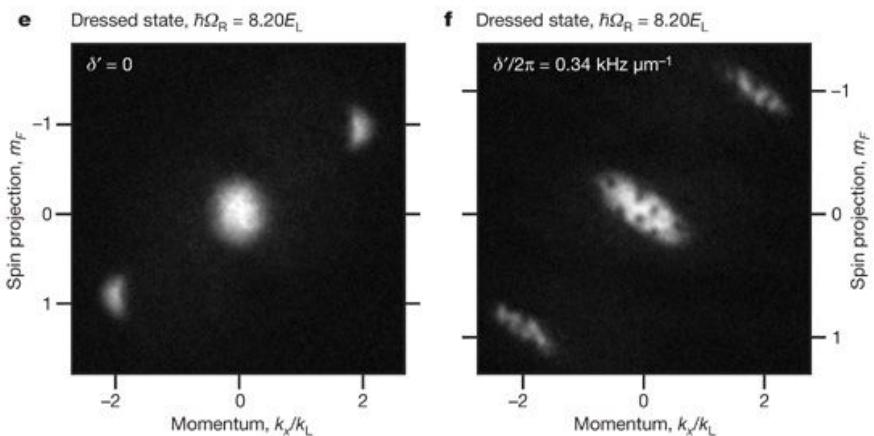
Rotation, Turbulence, Transport,
Impurities, Lower dimensions,

- 2006



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

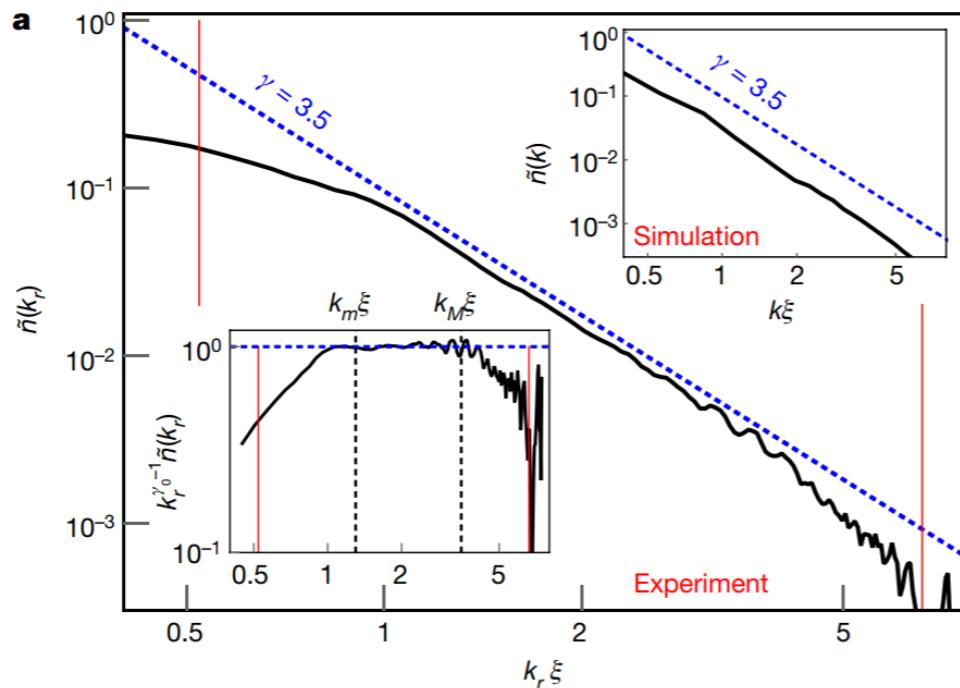
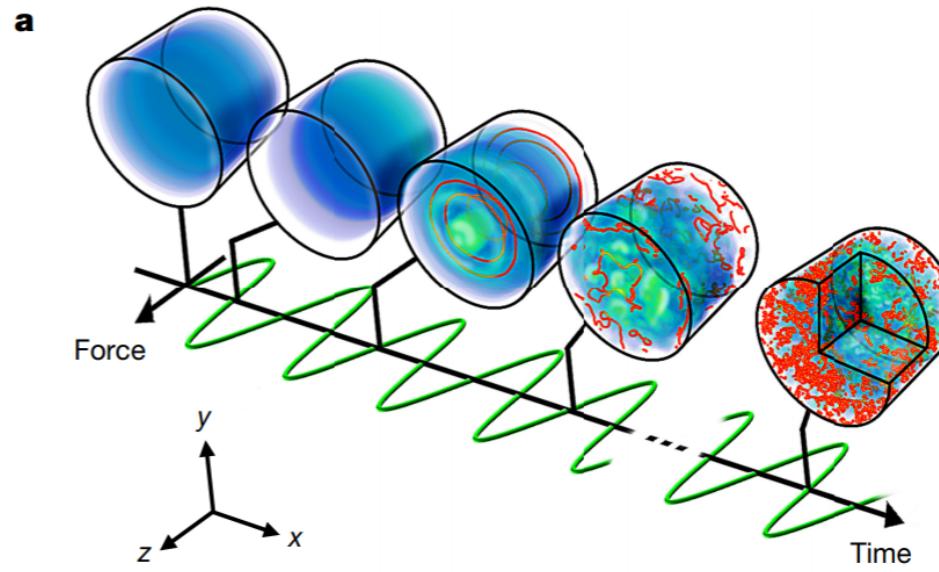
- 2009



Artificial
Gauge Fields
Spielman,
Nature 2009

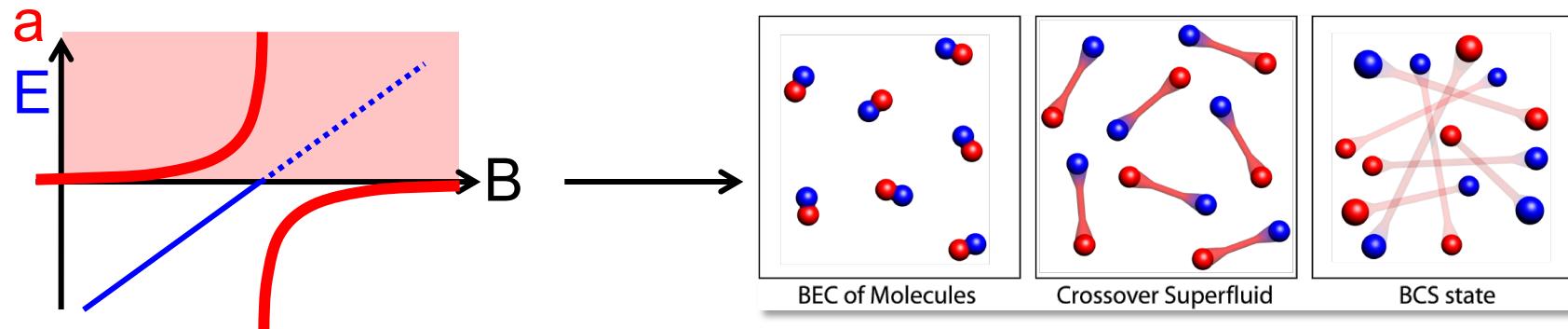
Studies on BECs (cont.): Turbulence

Hadzibabic,
Nature 2016



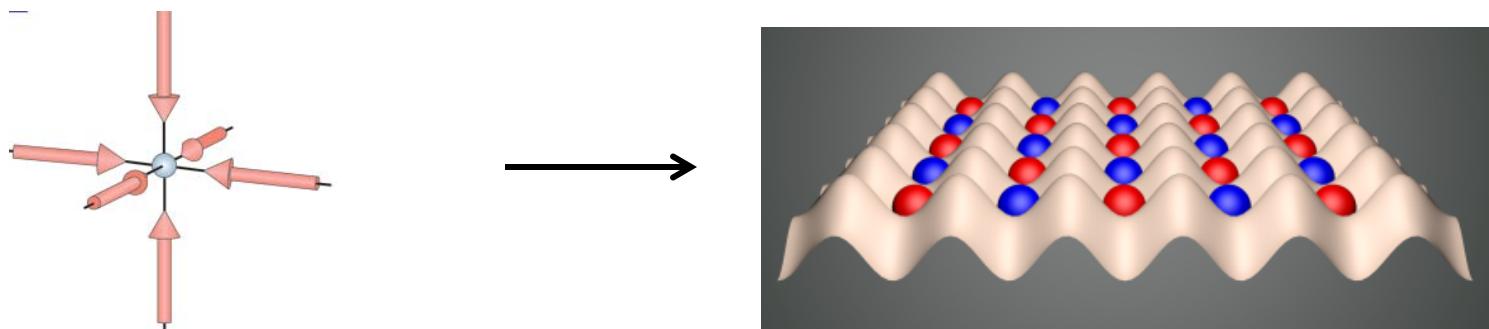
2001-now: strongly correlated states of matter

Feshbach Resonances \rightarrow e.g. BEC-BCS Crossover



Quantum Gases \rightarrow Quantum Fluids

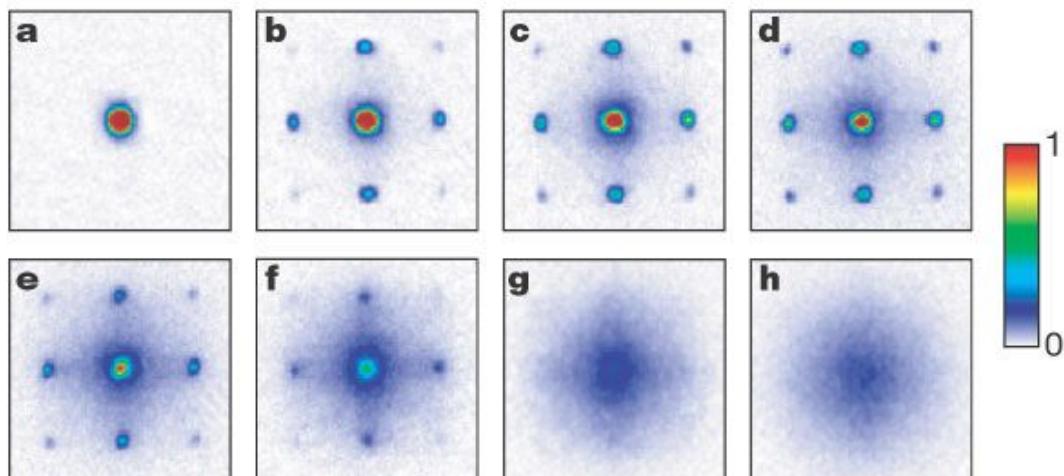
Optical Lattices \rightarrow e.g. Fermi-Hubbard model



Quantum Gases \rightarrow Quantum Solids

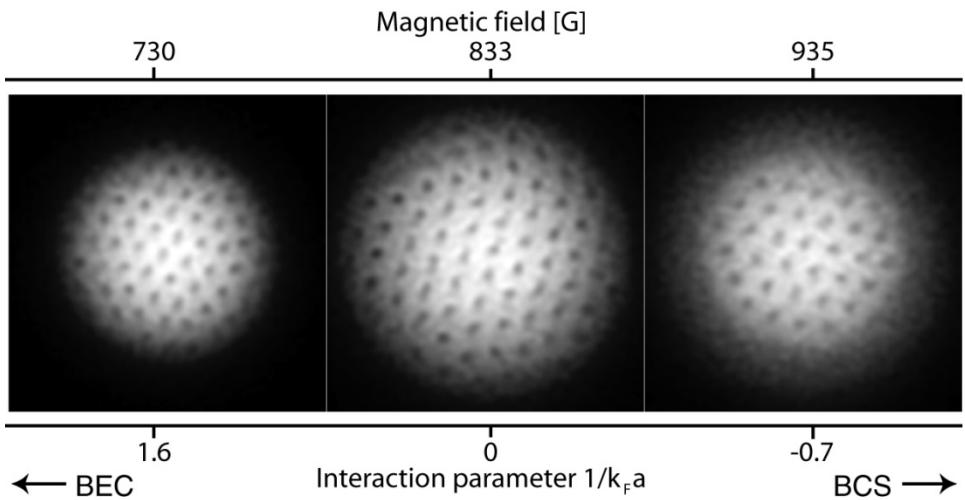
Strongly correlated states of matter

2001: Bosonic Mott Insulator



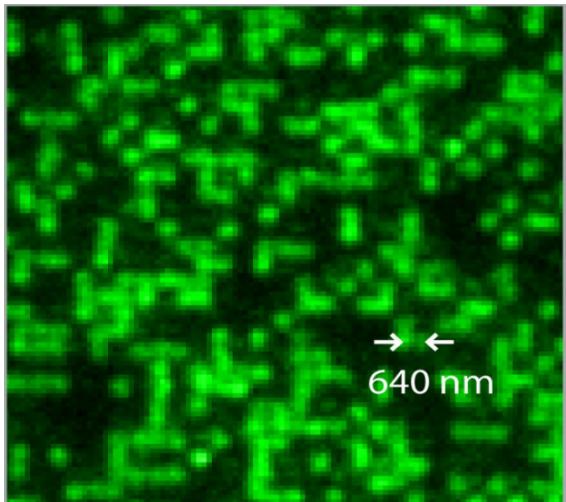
Greiner, Mandel, Esslinger, Hänsch, Bloch, Nature 2002

2005: Superfluidity in a Fermi gas



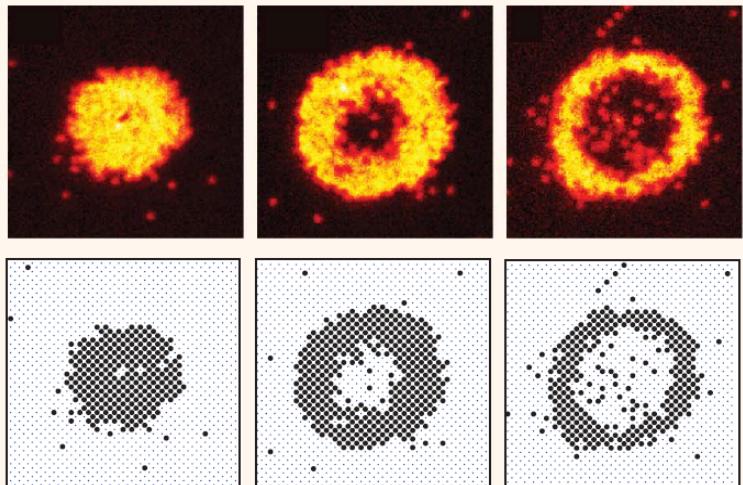
Zwierlein, Abo-Shaeer, Schirotzek, Schunck, Ketterle, Nature 2005

Quantum Gas Microscopes



Bosons
 ^{87}Rb

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

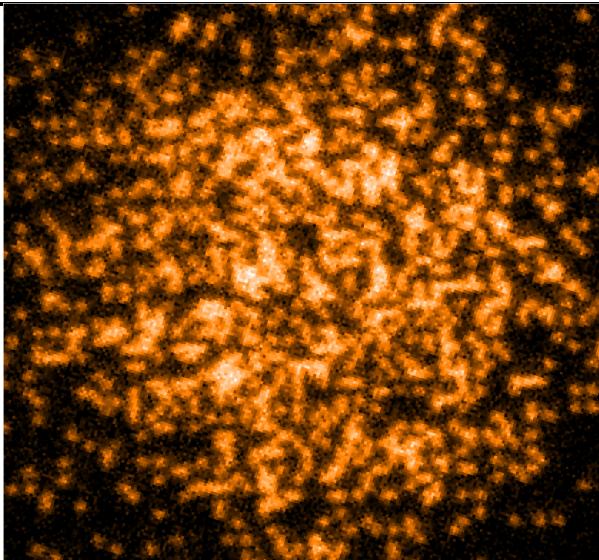


Sherson et al., Nature 467, 68-71 (2010)

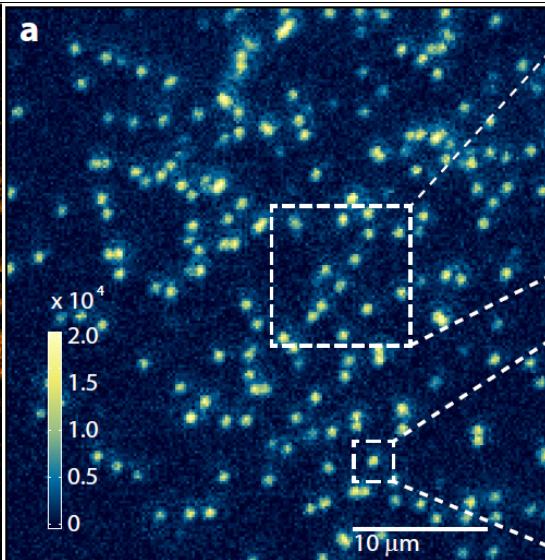
Also: ^{174}Yb bosons, Miranda et al., PRA 91, 063414 (2015)
Yamamoto et al., NJP 18, 023016 (2016)

Fermi Gas Microscopes

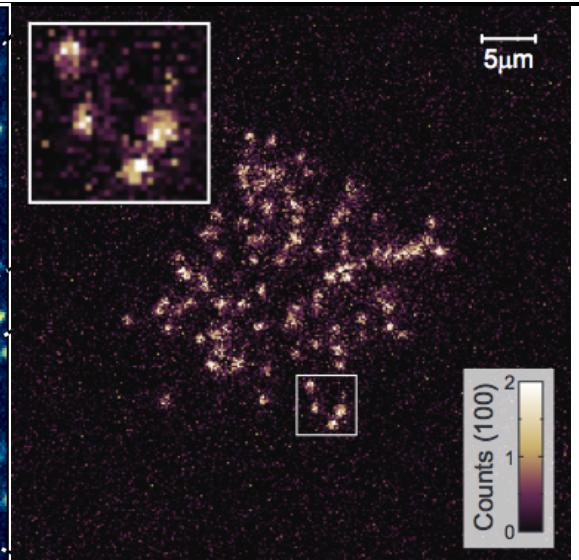
40K



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

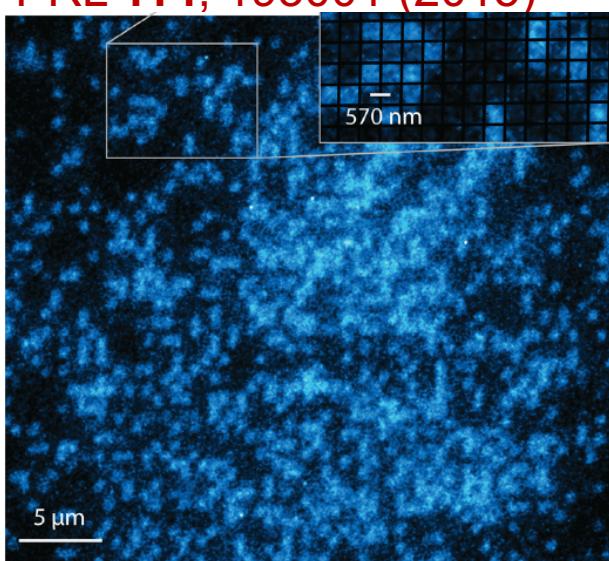


Kuhr group, Strathclyde
Nat. Phys. **11**, 738 (2015)

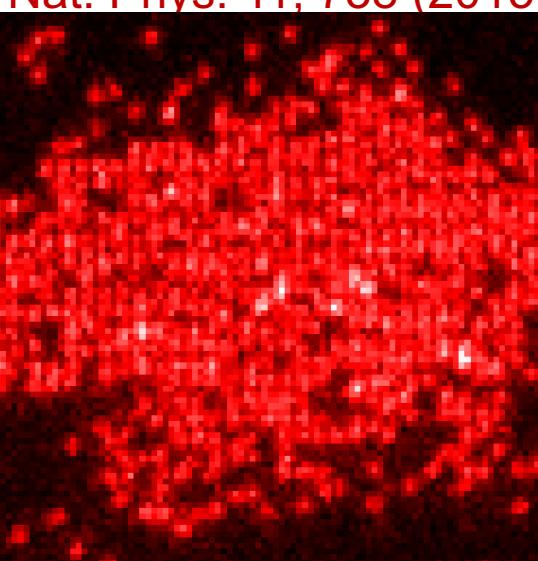


Thywissen group, Toronto,
PRA **92**, 063406 (2015)

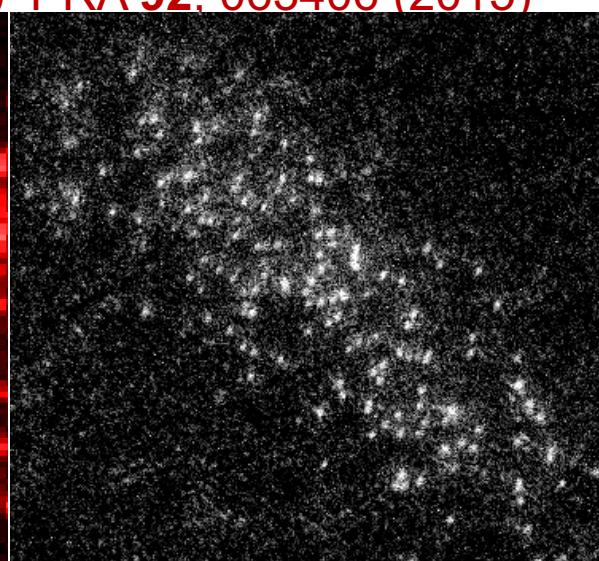
6Li



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



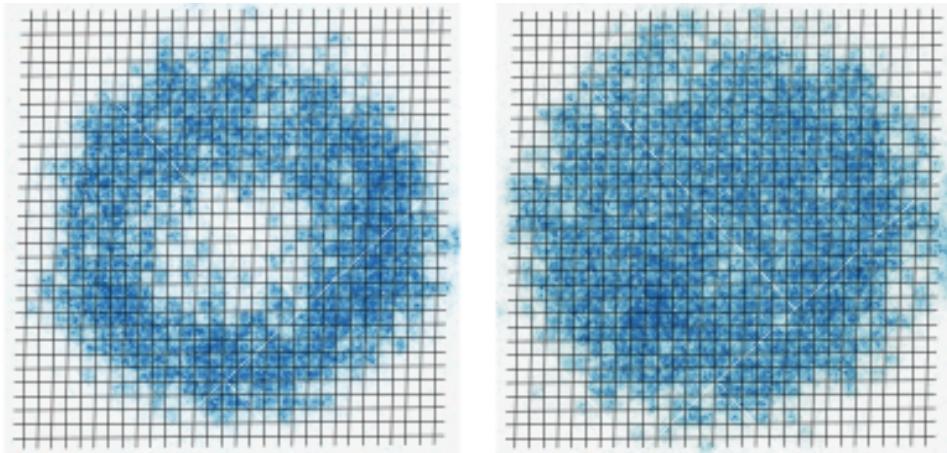
Gross/Bloch group, MPQ
PRL **115**, 263001 (2015)



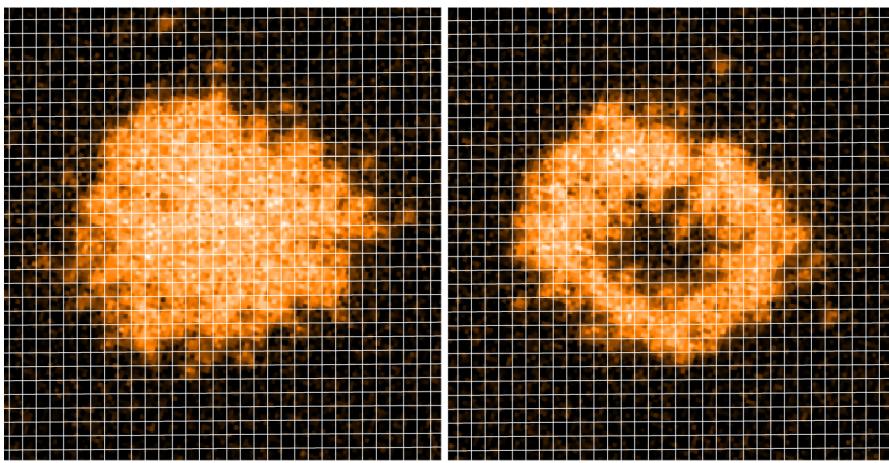
Bakr group, Princeton
ultracold.princeton.edu

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

${}^6\text{Li}$

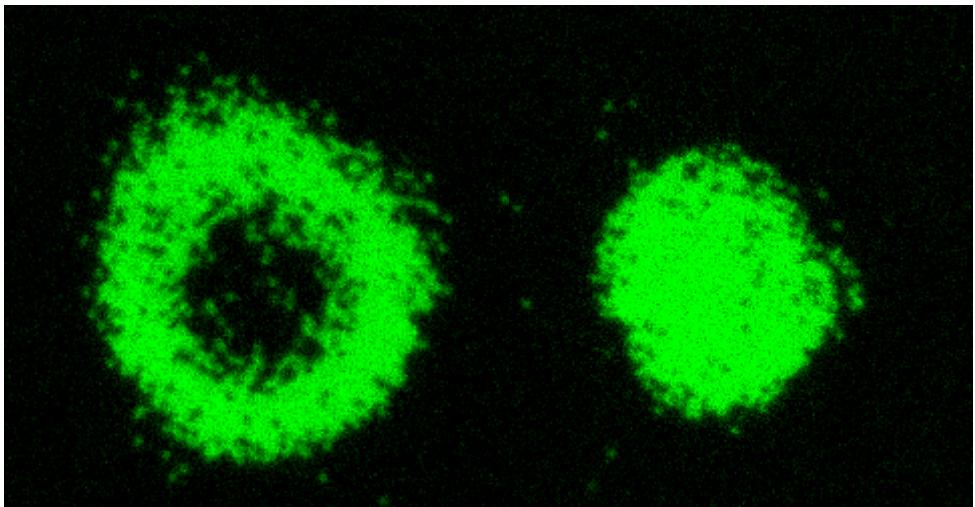


${}^{40}\text{K}$

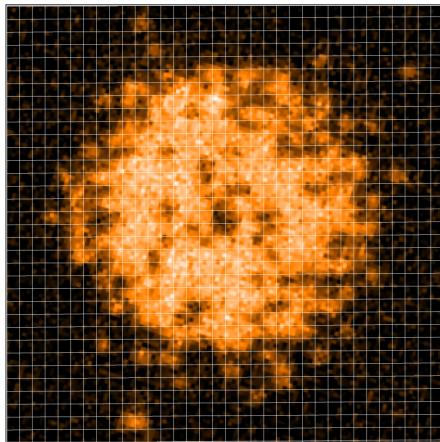


D. Greif et al,
Science **351** 953-957 (2016)

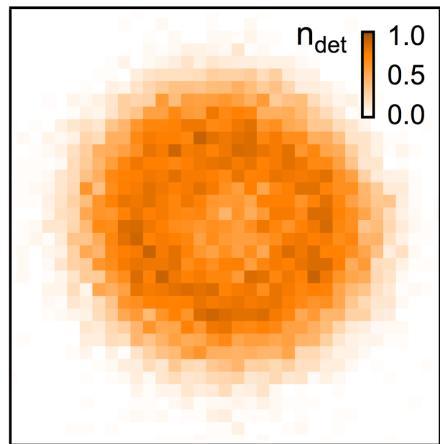
L.W. Cheuk, M.A. Nichols,
K. Lawrence, M. Okan,
H. Zhang, MWZ,
PRL **116**, 235301 (2016)



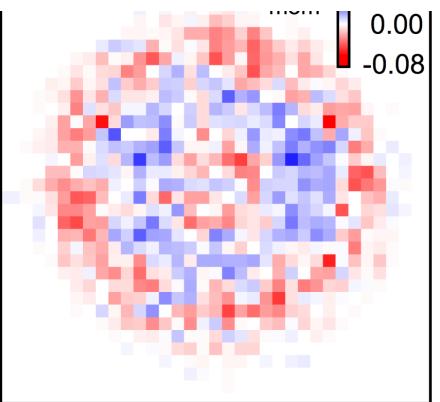
Direct Observation of Fermion Correlations



Single Shot

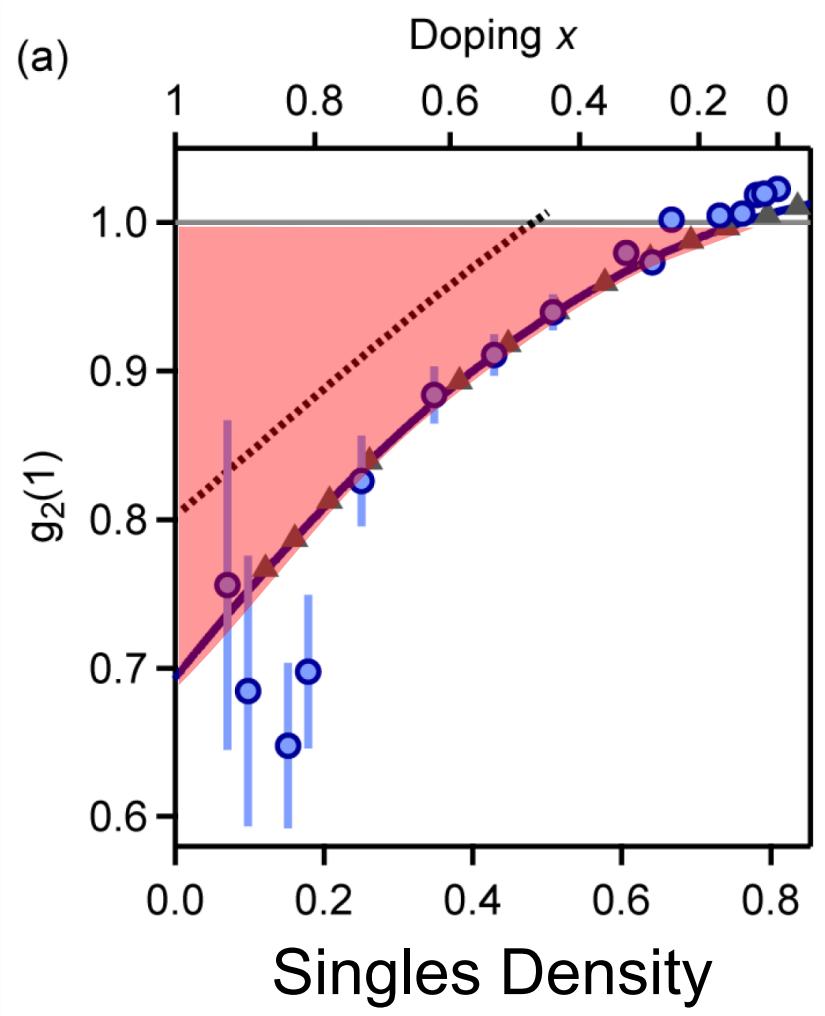


Average



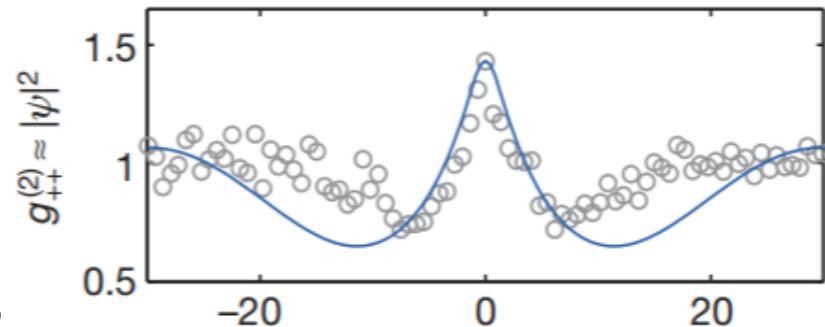
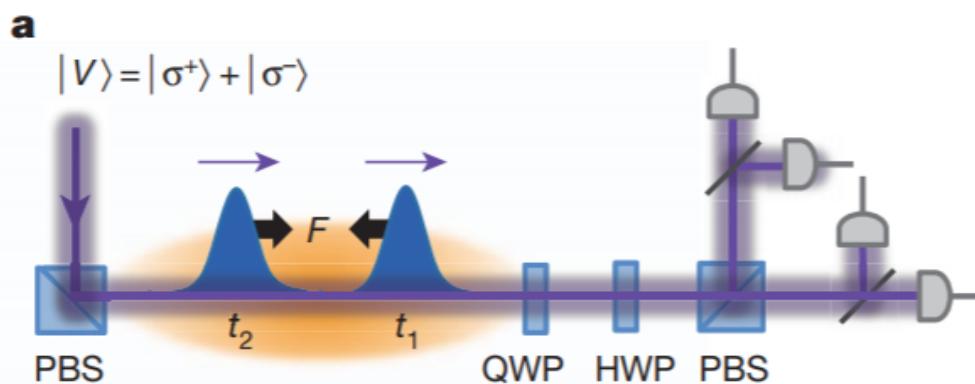
Correlations

Fermions stay away from each other:



Interacting Photons

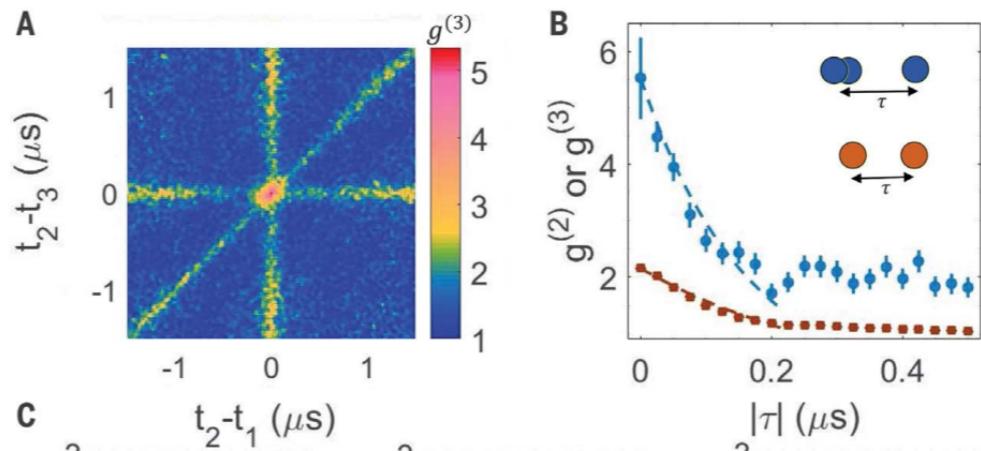
2013 Attractive photons in a non-linear medium (Rydbergs)



Firstenberg, ..., Lukin, Vuletic, Nature 2013

2018 Three-Photon bound states

Liang, ... Lukin, Vuletic, Science 2018

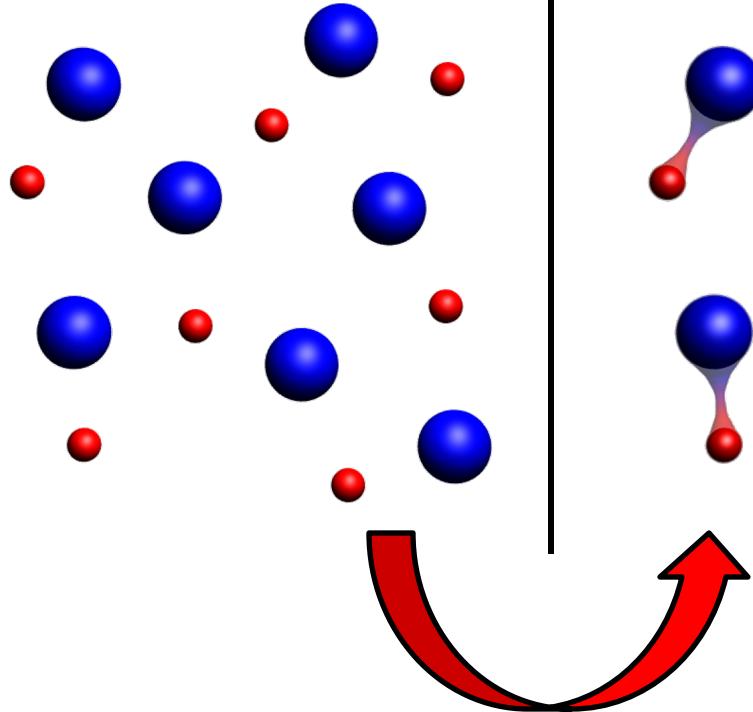


From Ultracold Atoms to Ultracold Molecules

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

Near-degenerate gas of
NaK Feshbach Molecules

Near-degenerate gas of
ground-state molecules

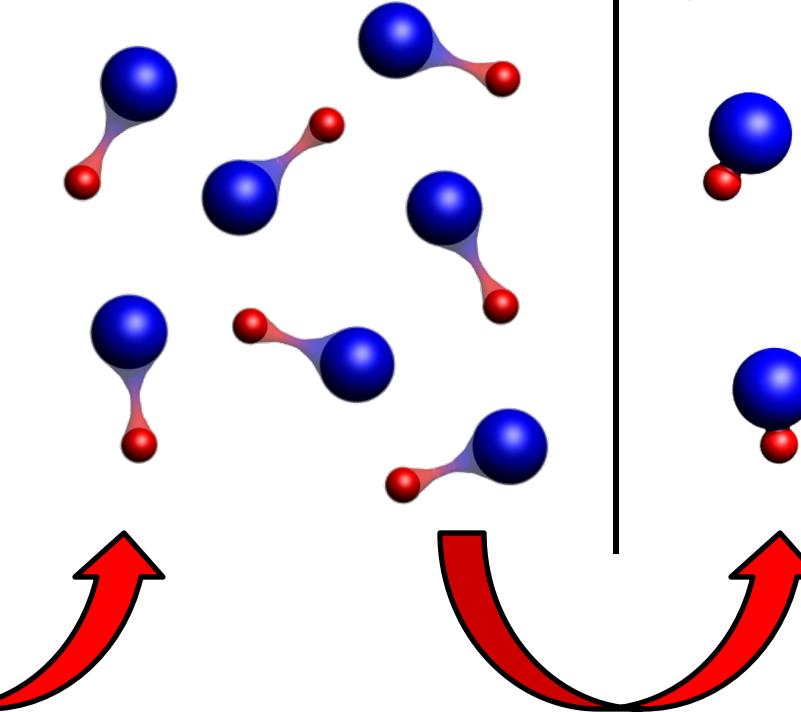


Feshbach Association

Binding energy 100 kHz

Internuclear Distance $300 \text{ } a_0$

Dipole Moment $5 \times 10^{-11} \text{ D}$



Raman Transfer (STIRAP)

→ Binding energy 150 THz $\sim 0.6 \text{ eV}$

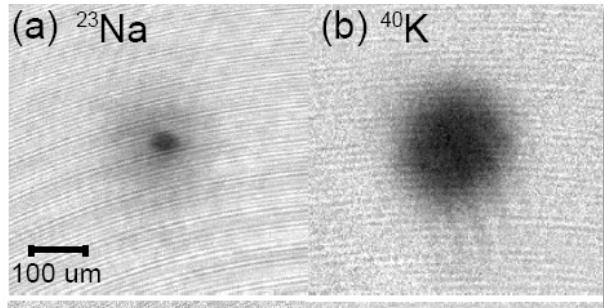
→ Internuclear Distance $7 \text{ } a_0$

→ 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)

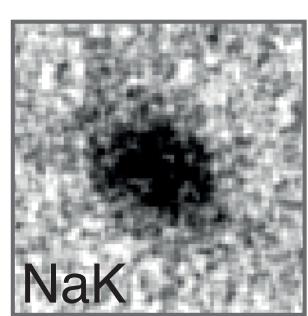
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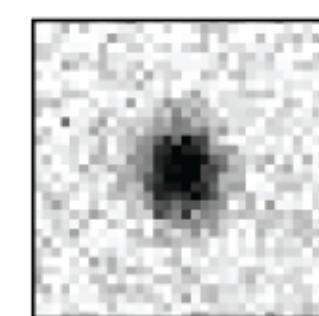
J.W. Park, C.-H. Wu,
I. Santiago, T. Tiecke,
P. Ahmadi, MWZ,
PRA(R) 85, 051602 (2012)

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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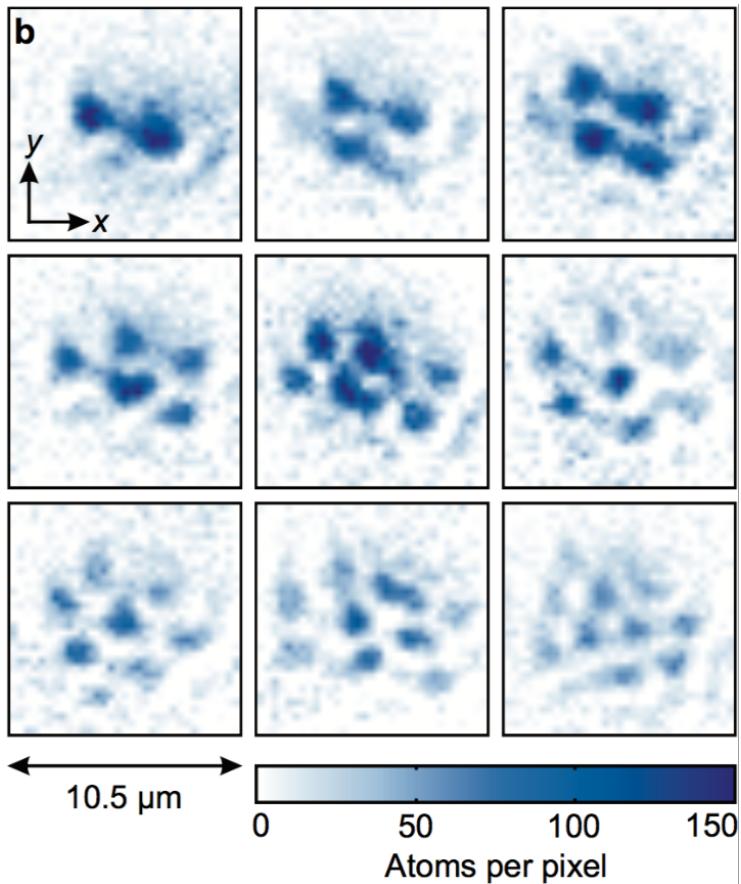
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Pioneering work with KRb and Cs₂: K. K. Ni et al., Science 322, 231 (2008)
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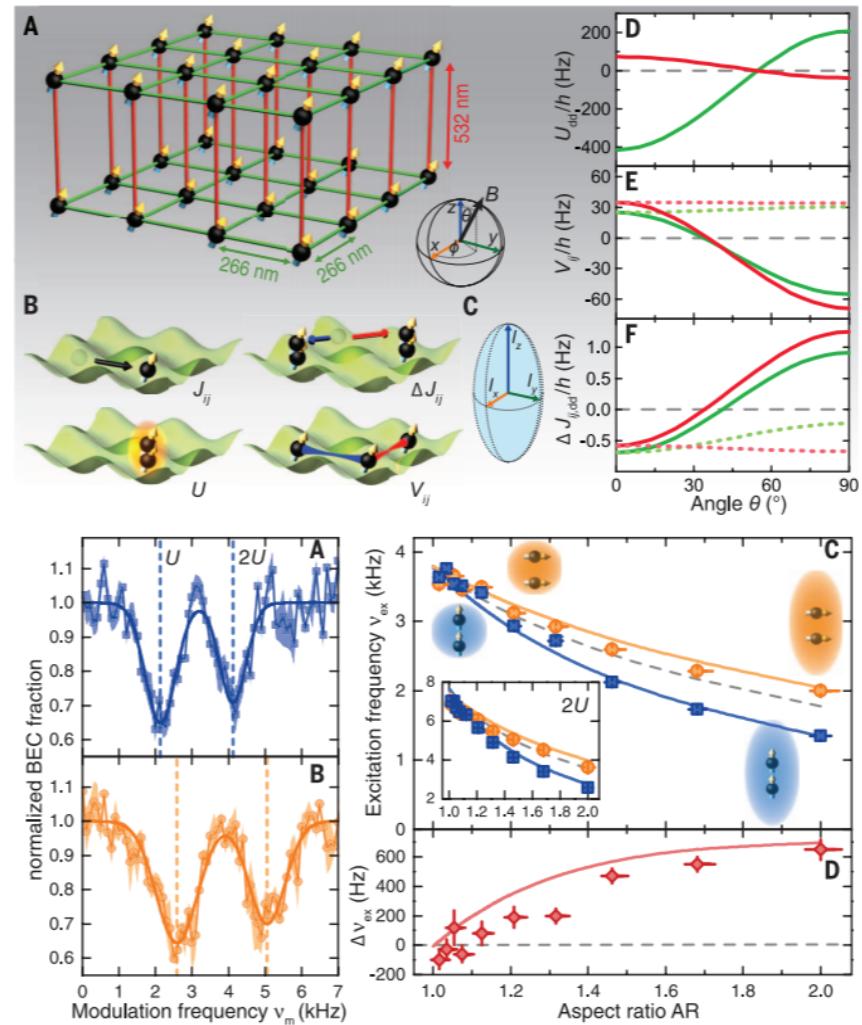
Dipolar Quantum Gases

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. Famà¹, A. Fioretti¹, C. Gabbanini¹, 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,*}

¹Institut für Experimentalphysik, Universität Innsbruck, Technikerstraße 25, 6020 Innsbruck, Austria

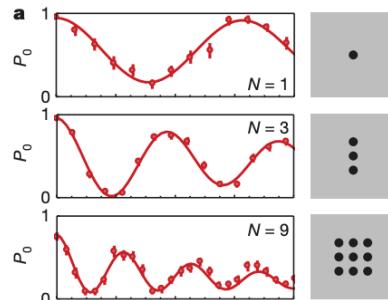
²Institut für Quantenoptik und Quanteninformation, Österreichische Akademie der Wissenschaften, Technikerstraße 21a, 6020 Innsbruck, Austria

Quantum Computation & Simulation

Browaeys group, Paris, Nature 2016

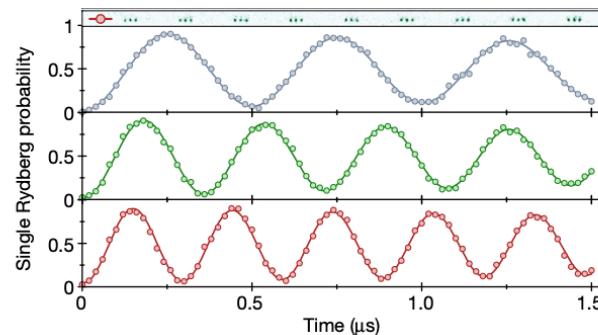
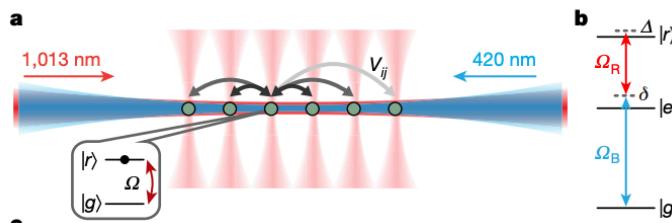
Tunable two-dimensional arrays of single Rydberg atoms for realizing quantum Ising models

Henning Labuhn^{1*}, Daniel Barredo^{1*}, Sylvain Ravets¹, Sylvain de Léséleuc¹, Tommaso Macrì², Thierry Lahaye¹ & Antoine Browaeys¹



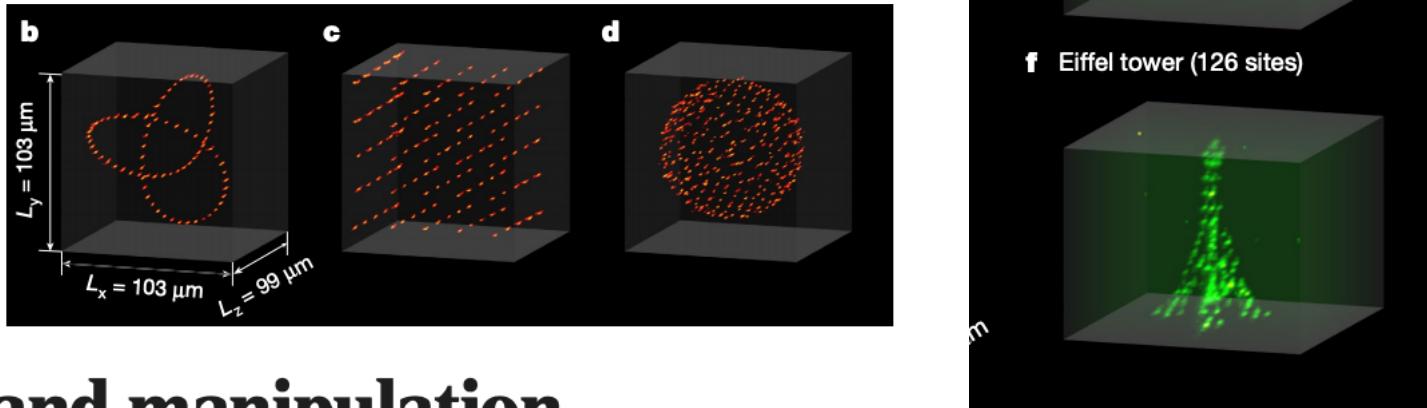
Probing many-body dynamics on a 51-atom quantum simulator

Hannes Bernien¹, Sylvain Schwartz^{1,2}, Alexander Keesling¹, Harry Levine¹, Ahmed Omran¹, Hannes Pichler^{1,3}, Soonwon Choi¹, Alexander S. Zibrov¹, Manuel Endres⁴, Markus Greiner¹, Vladan Vuletić² & Mikhail D. Lukin¹



Synthetic three-dimensional atomic structures assembled atom by atom

Daniel Barredo^{1,2*}, Vincent Lienhard^{1,2}, Sylvain de Léséleuc^{1,2}, Thierry Lahaye¹ & Antoine Browaeys¹



Generation and manipulation of Schrödinger cat states in Rydberg atom arrays

A. Omran^{1*}, H. Levine^{1*}, A. Keesling¹, G. Semeghini¹, T. T. Wang^{1,2}, S. Ebadi¹, H. Bernien³, A. S. Zibrov¹, H. Pichler^{1,4}, S. Choi⁵, J. Cui⁶, M. Rossignolo⁷, P. Rembold⁶, S. Montangero⁸, T. Calarco^{6,9}, M. Endres¹⁰, M. Greiner¹, V. Vuletić¹¹, M. D. Lukin^{1†}

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

Alexander Keesling¹, Ahmed Omran¹, Harry Levine¹, Hannes Bernien¹, Hannes Pichler^{1,2}, Soonwon Choi¹, Rhine Samajdar¹, Sylvain Schwartz³, Pietro Silvi^{4,5}, Subir Sachdev¹, Peter Zoller^{4,5}, Manuel Endres⁶, Markus Greiner¹, Vladan Vuletić⁷ & 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...