22nd December 2025 KAIS-SNU winter school

Ultracold atomic quantum simulator

Realizing Feynman's dream

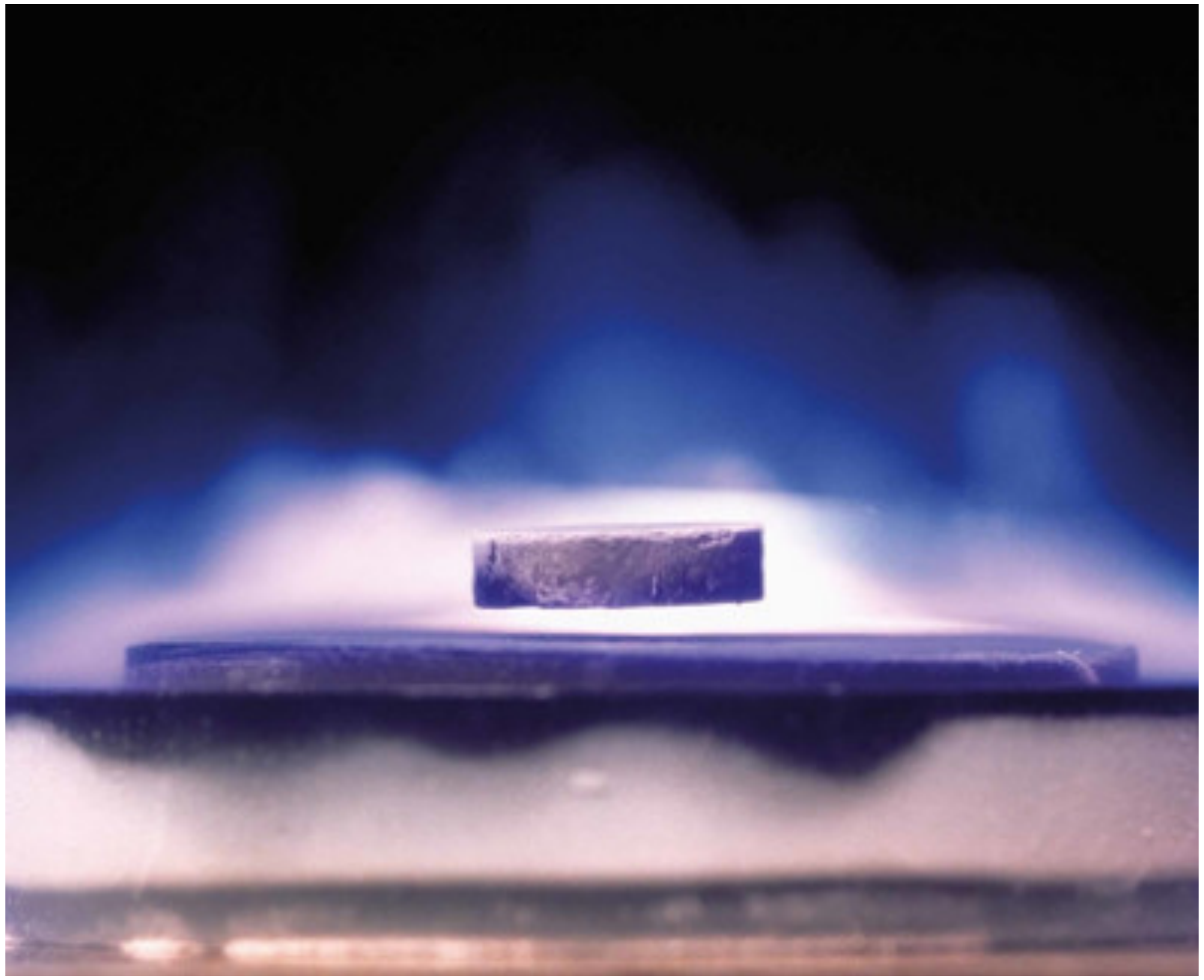
Jae-yoon Choi (KAIST, Physics department)

National Research Foundation of Korea

Motivations

Understand and Design novel quantum material

One of the biggest challenge of modern condensed matter physics



High temperature superconductivity

Condensed Matter > Superconductivity

[Submitted on 22 Jul 2023]

The First Room-Temperature Ambient-Pressure Superconductor

Sukbae Lee, Ji-Hoon Kim, Young-Wan Kwon

PHYSICAL REVIEW B **108**, 235127 (2023)

Editors' Suggestion

$Pb_9Cu(PO_4)_6(OH)_2$: Phonon bands, localized flat-band magnetism, models, and chemical analysis

Yi Jiang,[1,*] Scott B. Lee,[2,*] Jonah Herzog-Arbeitman,[3,*] Jiabin Yu,[3,*] Xiaolong Feng,[4,*] Haoyu Hu,[1,*] Dumitru Călugăru,[3,*] Parker S. Brodale,[5,*] Eoghan L. Gormley,[5,*] Maia G. Vergniory,[1,4] Claudia Felser,[4] S. Blanco-Canosa,[1,6] Christopher H. Hendon,[5] Leslie M. Schoop,[2,*] and B. Andrei Bernevig[1,3,6,*]

[1]*Donostia International Physics Center (DIPC), P. Manuel de Lardizabal 4, 20018 Donostia-San Sebastian, Spain*
[2]*Department of Chemistry, Princeton University, Princeton, New Jersey 08544, USA*
[3]*Department of Physics, Princeton University, Princeton, New Jersey 08544, USA*
[4]*Max Planck Institute for Chemical Physics of Solids, 01187 Dresden, Germany*
[5]*Department of Chemistry and Biochemistry, University of Oregon, Eugene, Oregon 97403, USA*
[6]*IKERBASQUE, Basque Foundation for Science, 48013 Bilbao, Spain*

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NEWS | 16 August 2023

LK-99 scienc

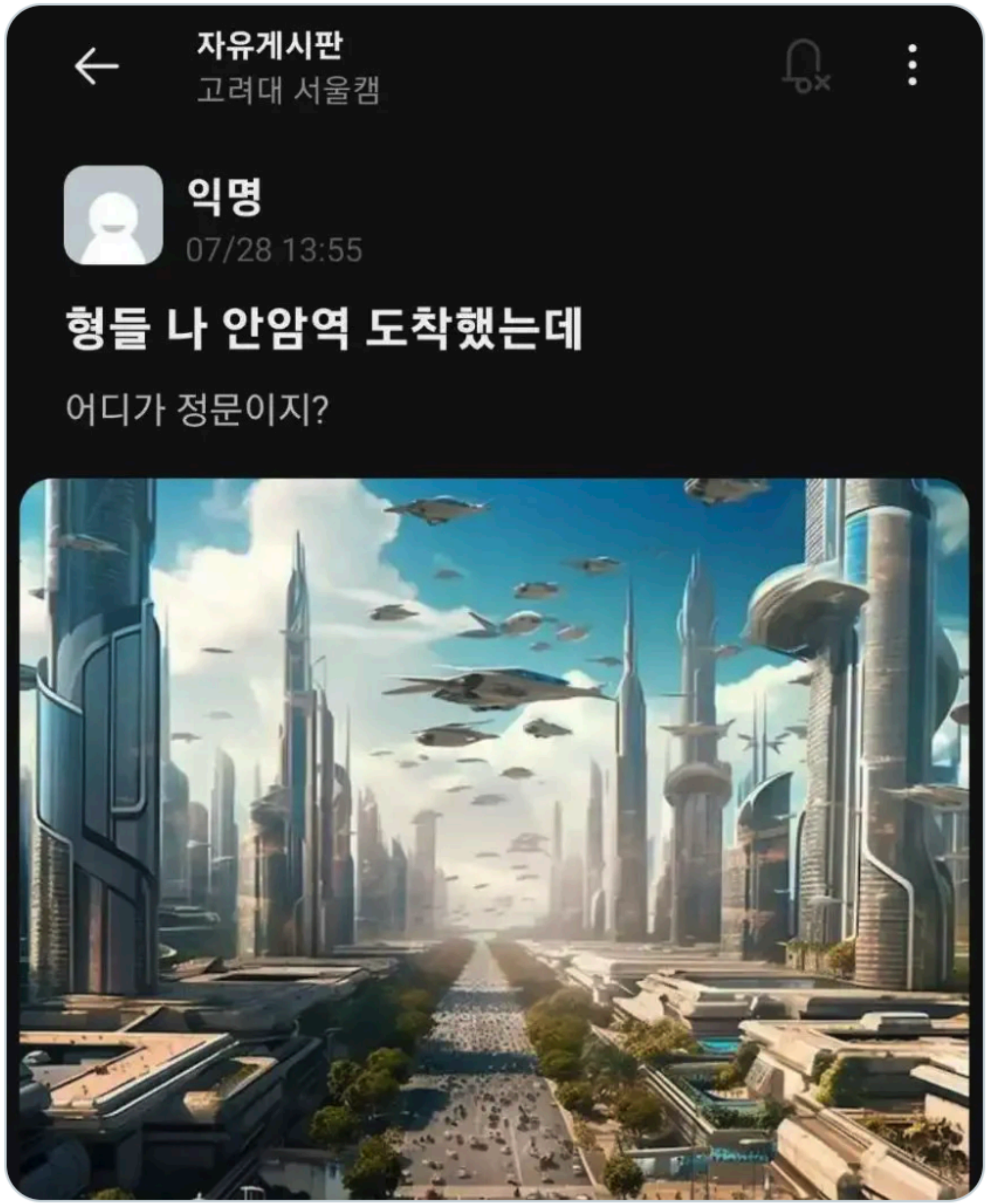
Efforts to repl superconduc

경제

뉴욕매거진 "LK-99는 초전도체"

최승호 기자 sisamirae79@naver.com | 등록 2024.01.21 21:56:55

오늘 장 요약


자유게시판
고려대 서울캠
익명
07/28 13:55
형들 나 안암역 도착했는데
어디가 정문이지?


발견 맞으면 교명 바꿔야됨
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도대학교
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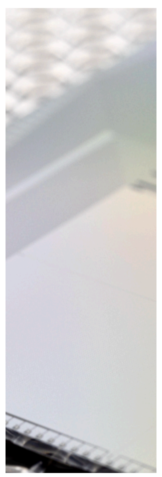
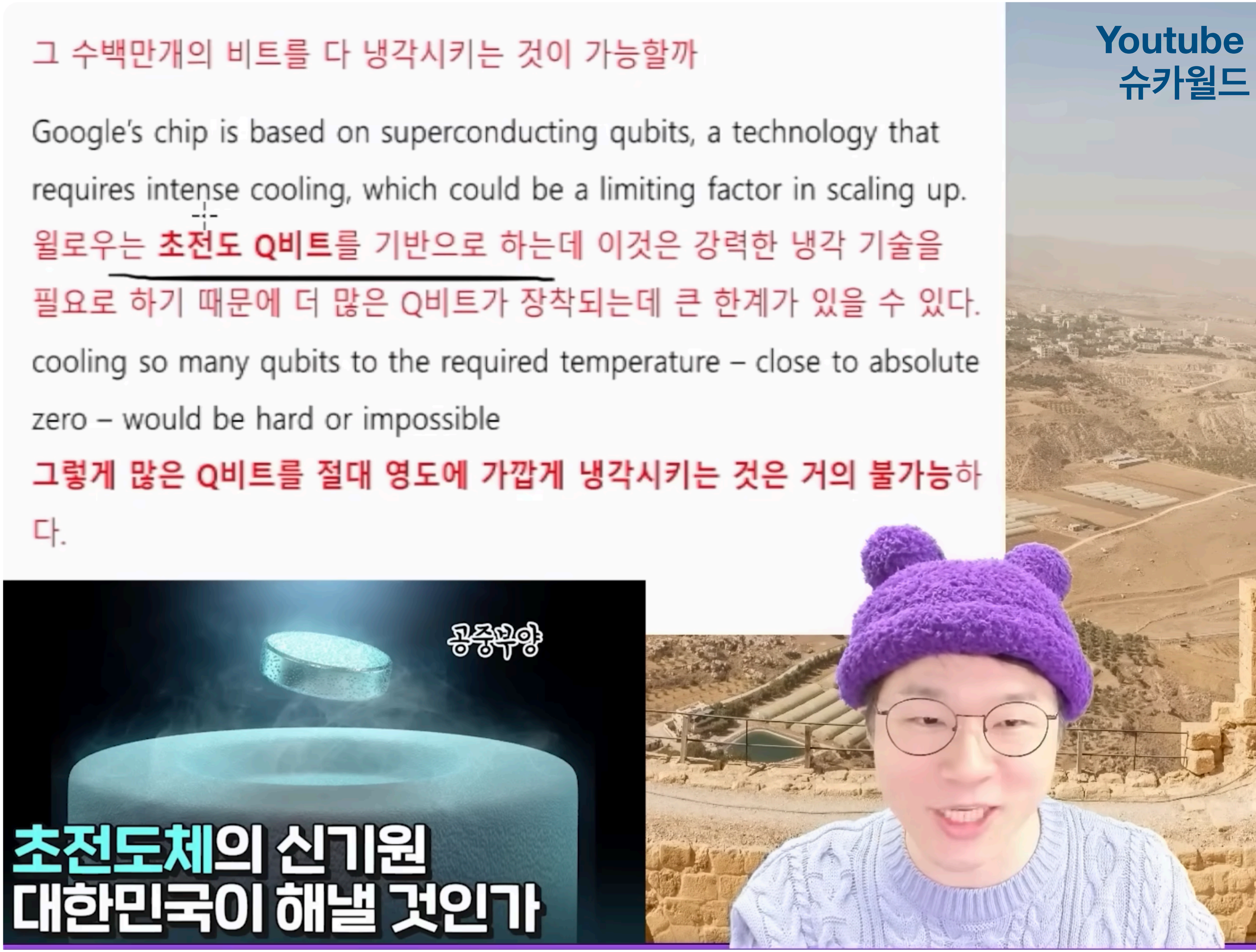
Motivations

Ma

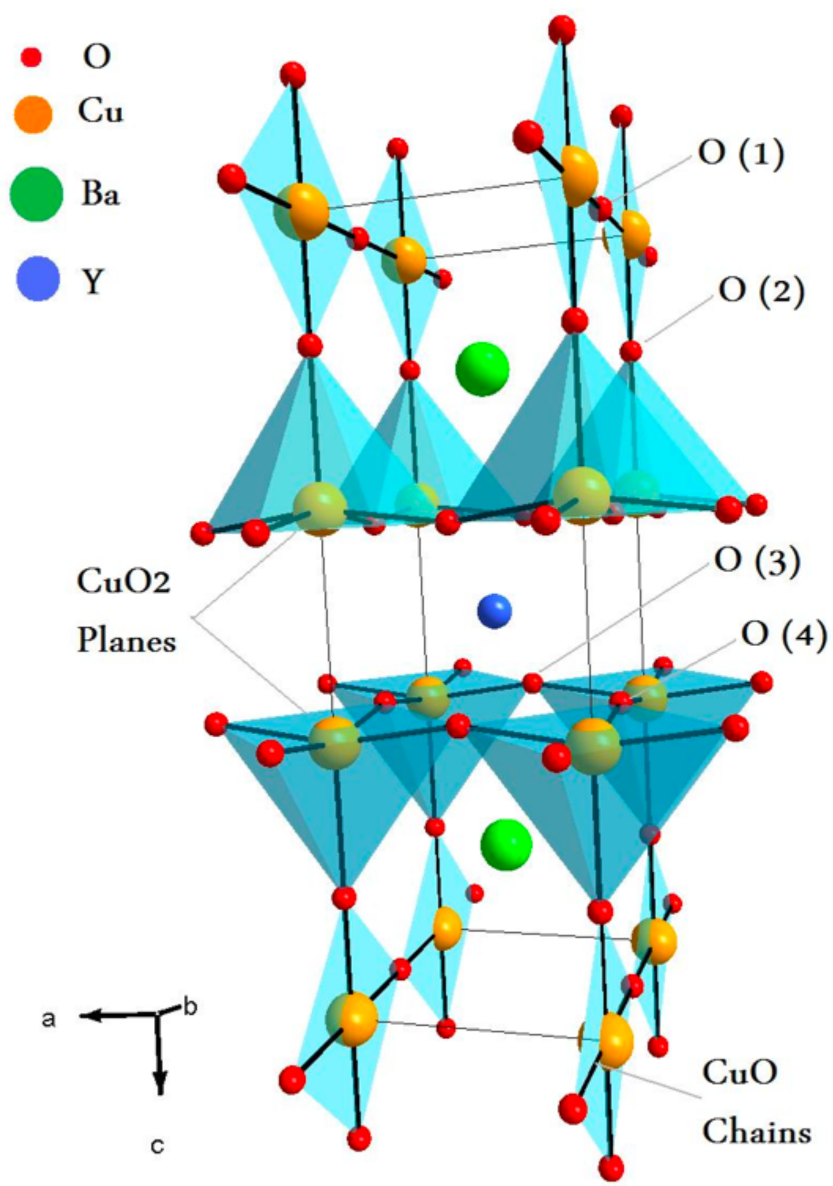




Motivations

Why it is difficult?

Many-body quantum problem is usually intractable with classical computers



a. Complex structures and lacks of experimental controllabilities

b. Strong interactions and limits of perturbative approaches

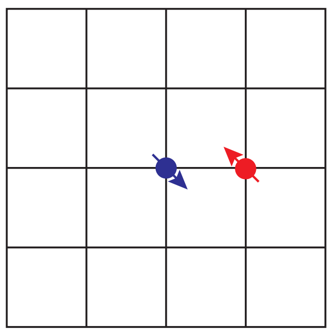
c. Even the simple model has no exact solution

$$H = -t \sum_{(i,j),\sigma} \hat{c}^{\dagger}_{i\sigma} \hat{c}_{j\sigma} + V \sum_{i,\sigma,\sigma'} \hat{c}^{\dagger}_{i\sigma} \hat{c}^{\dagger}_{i\sigma'} \hat{c}_{i\sigma'} \hat{c}_{i\sigma}$$

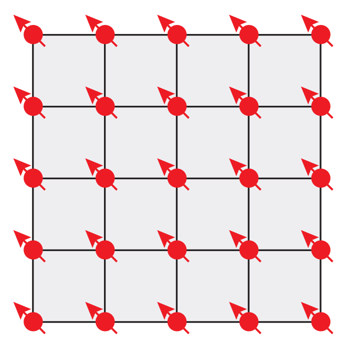
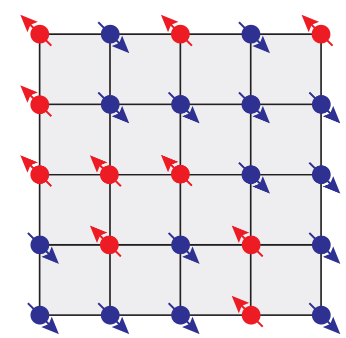
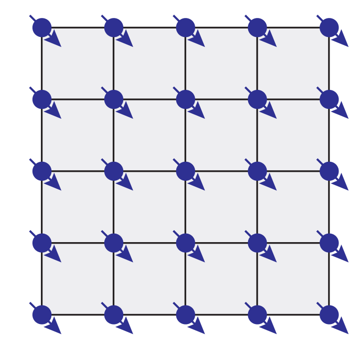
Fermi-Hubbard model

Quantum complexity

Hilbert space scales with exponential with the particle number



e.g. spin-1/2 in a square 2D lattice.

$|\Psi\rangle = c_1$  $+ c_2$  $\ldots + c_N$ 

Number of possible configuration 2^N

Motivations

State of the art ~ 40 spins (2D)

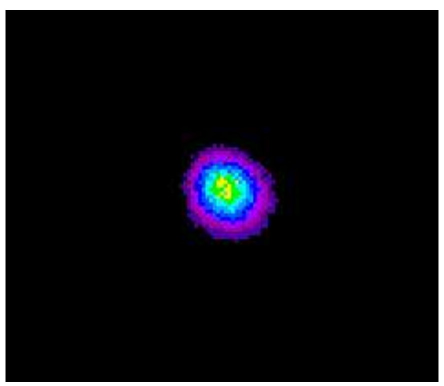
Adding SINGLE spin requires DOUBLING of the system

For N=300, 2^{300} : estimated number of protons in the universe

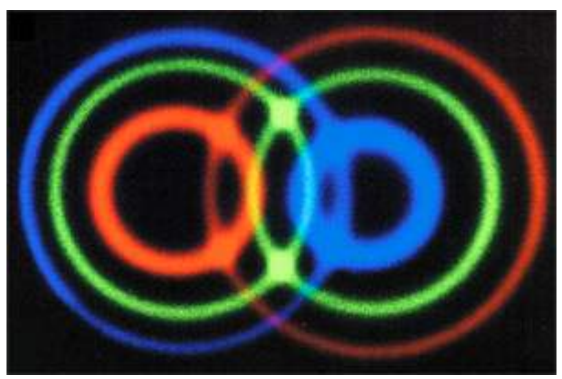
Atomic Molecular and Optical (AMO) physics

- Control of single and few particles
- Atoms/ions are identical and have long coherence

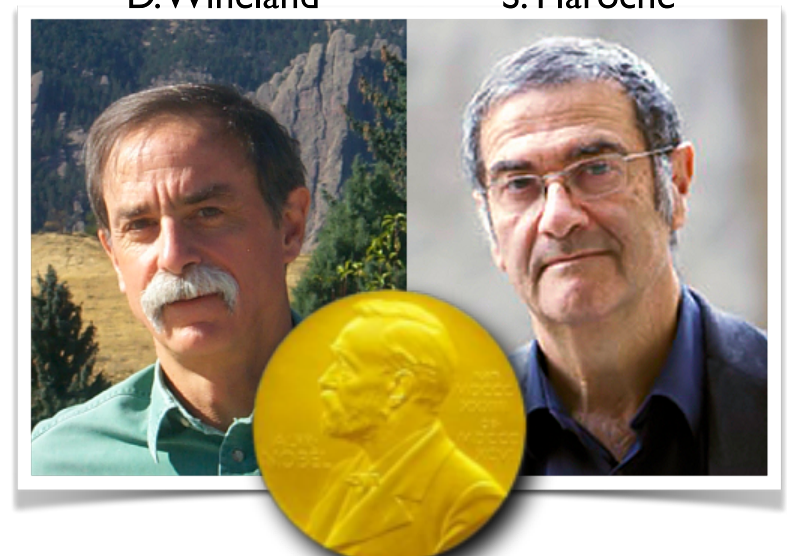
Single atom/ion



Photons



D. Wineland S. Haroche



Towards ultimate control of many-body quantum system

R. Feynman's Vision

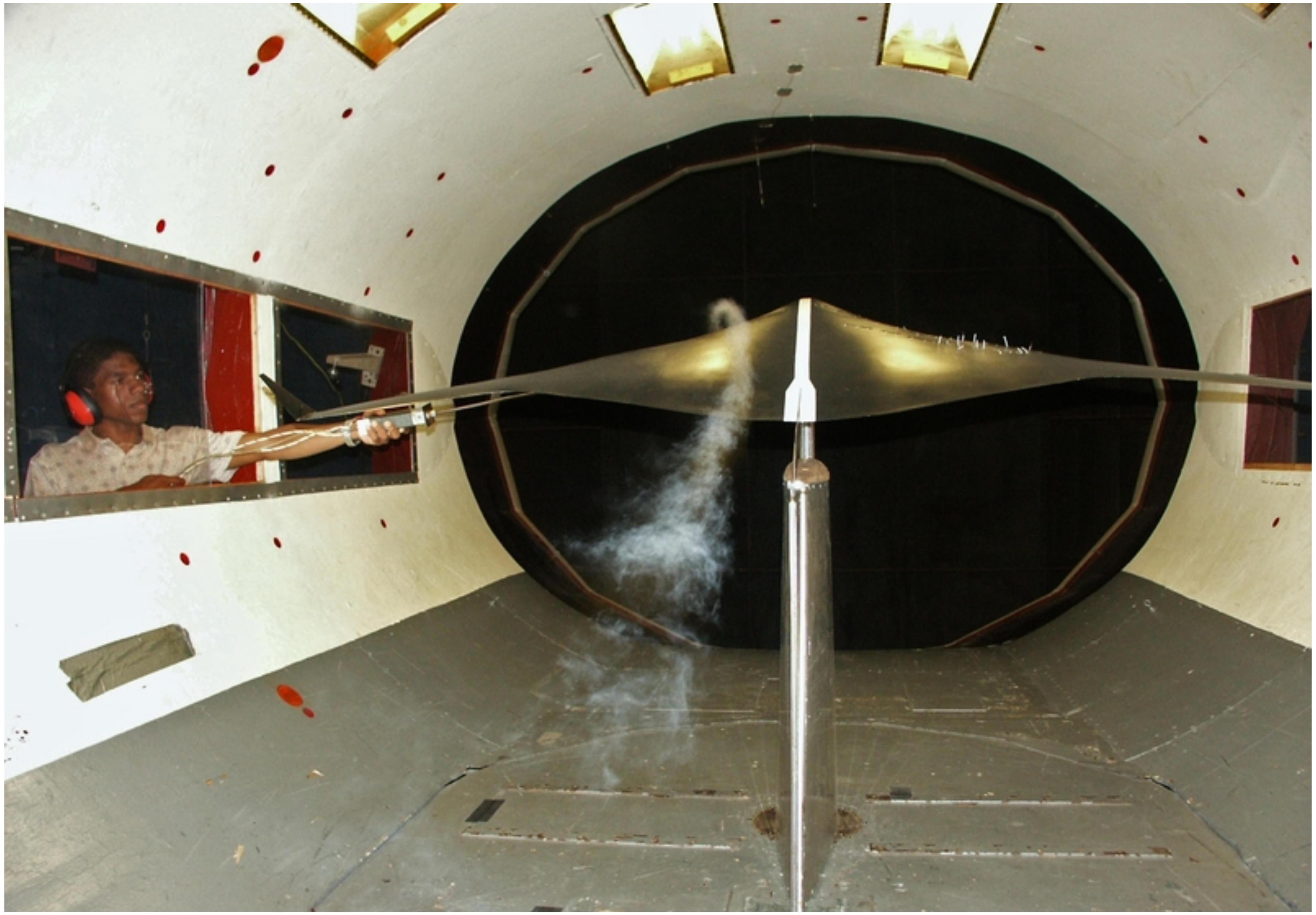
Build a quantum simulator that could imitate any quantum system

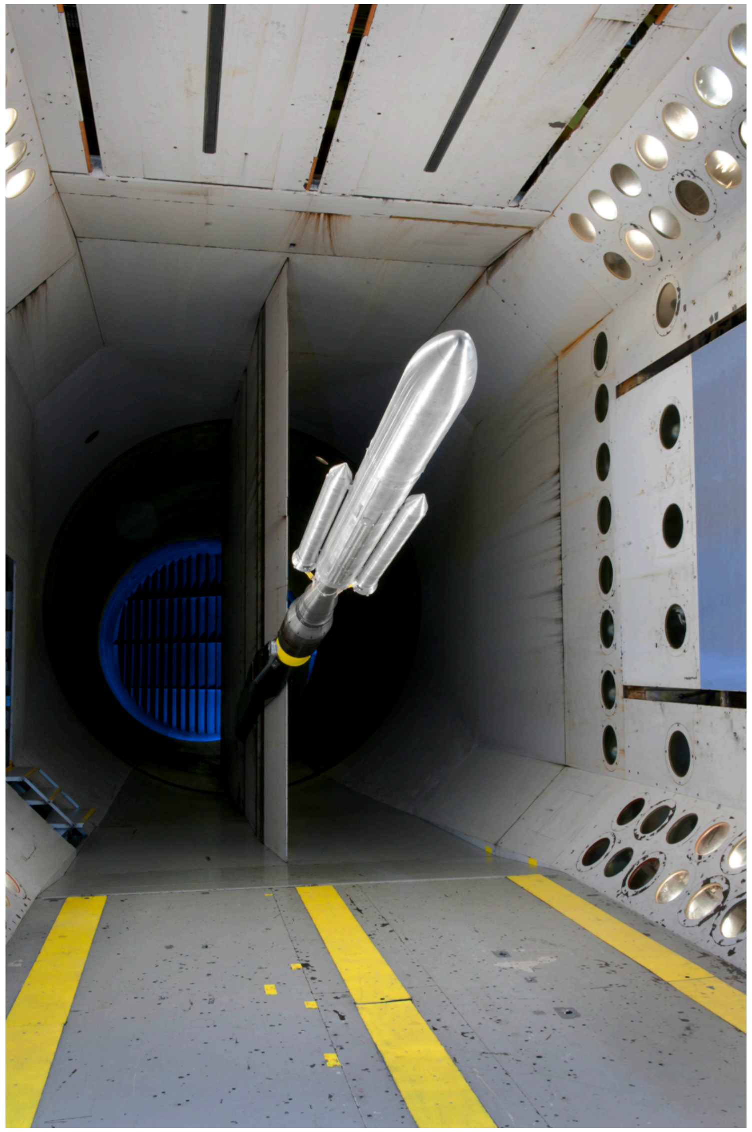
Advantage(?)

Perspective

Practical quantum advantage in quantum simulation

Nature **667**, 607 (2022)

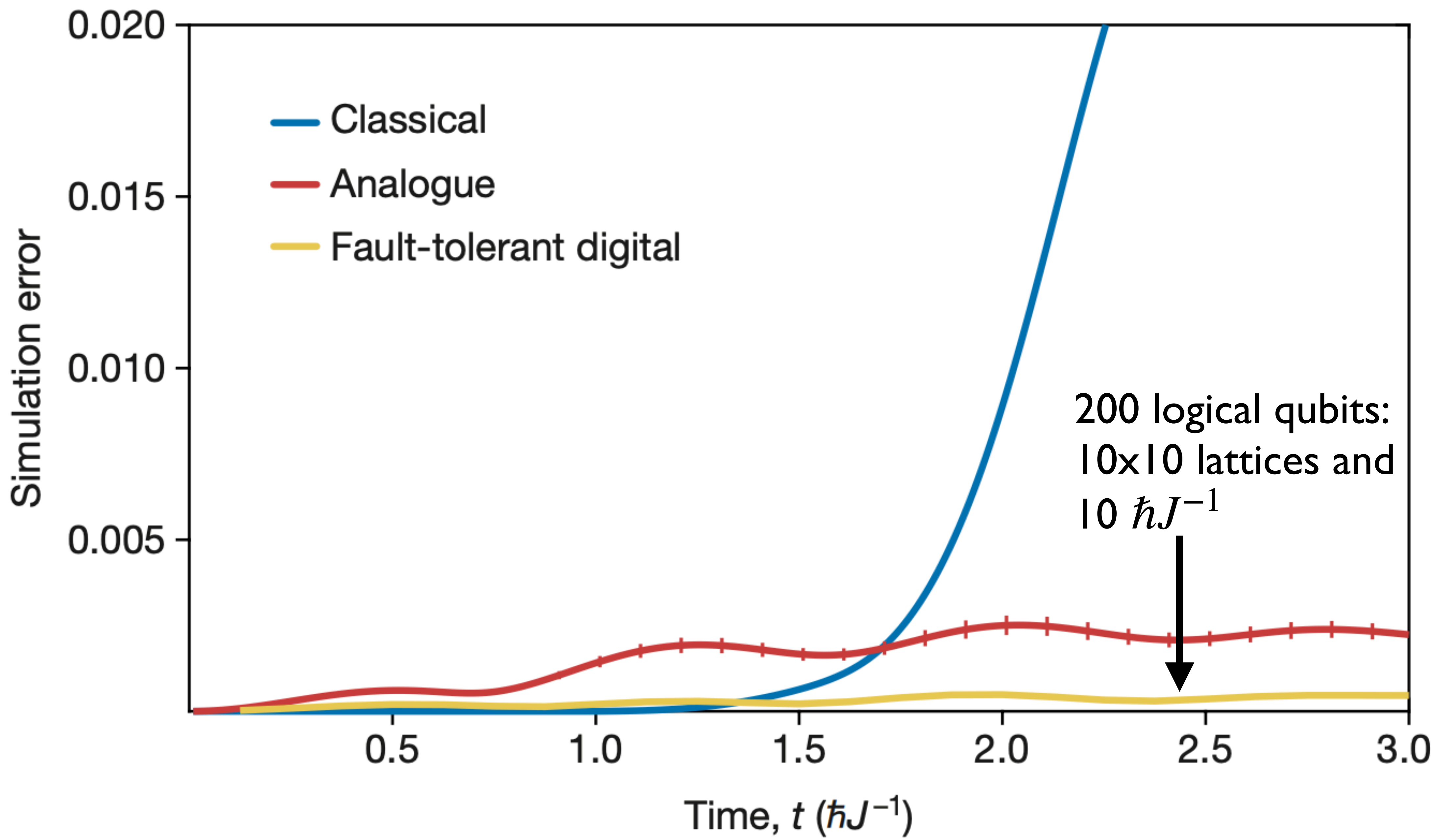




Advantage(?)

$$|\psi(t)\rangle = e^{-\frac{i}{\hbar}Ht}|\psi(0)\rangle$$

$$H = -t\sum_{(i,j),\sigma} \hat{c}^\dagger_{i\sigma}\hat{c}_{j\sigma} + V\sum_{i,\sigma,\sigma'} \hat{c}^\dagger_{i\sigma}\hat{c}^\dagger_{i\sigma'}\hat{c}_{i\sigma'}\hat{c}_{i\sigma}$$



Outline

Ultracold atoms; Bose-Einstein condensation

Atom-photon interactions

BECs in optical lattices

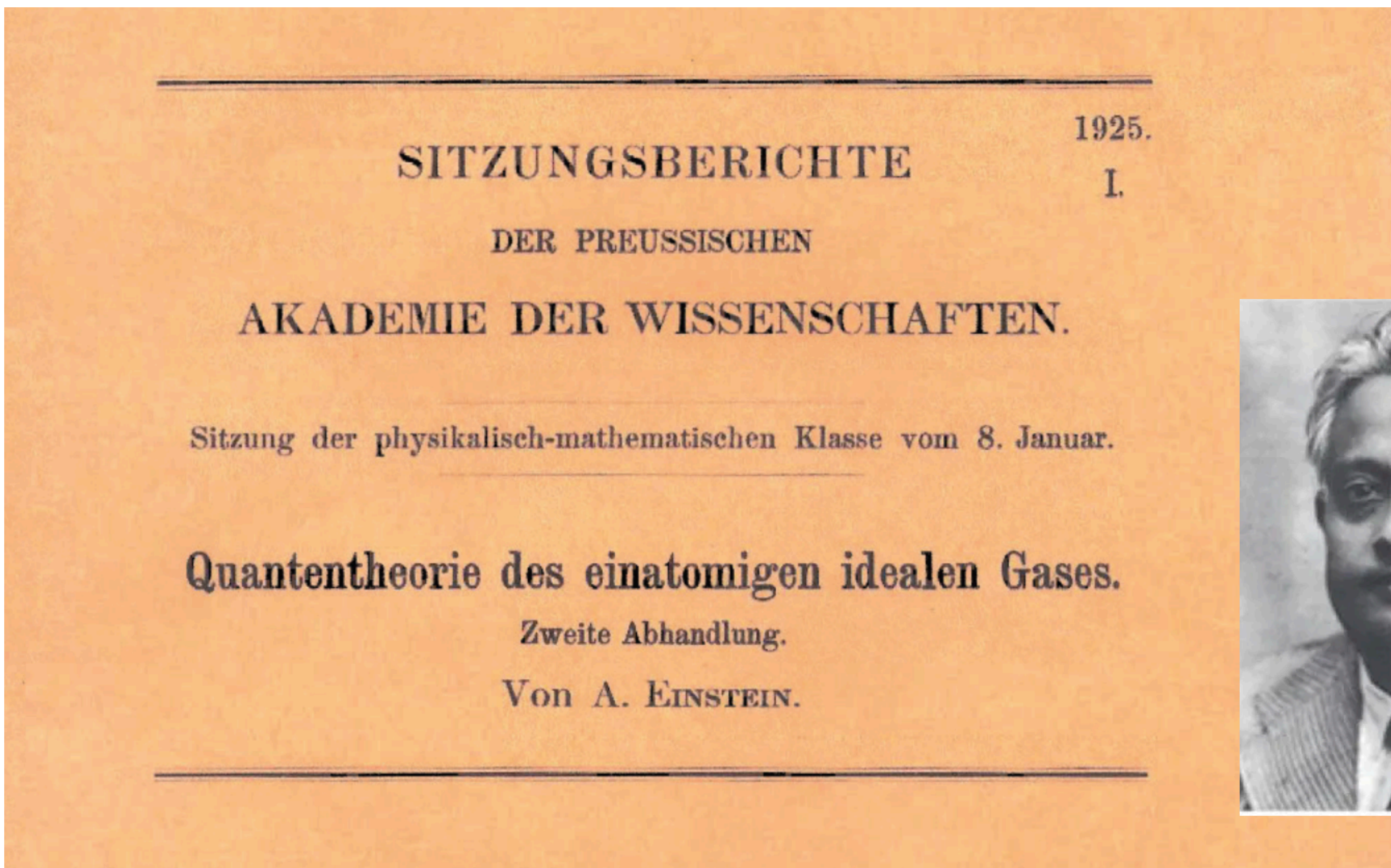
Atomic quantum simulator — many-body localization

100th anniversary of Bose-Einstein condensate

S. Bose, 1924: Derive the black-body radiation, notion of Bose statistics

$$E = \frac{8\pi \nu^2 d\nu}{c^3}\left[\frac{h\nu}{\exp\left(h\nu / k_B T\right) - 1}\right]$$

A. Einstein, 1924, 1925: Extended to a system with fixed massive Bose particles



1925.

I.

SITZUNGSBERICHTE

DER PREUSSISCHEN

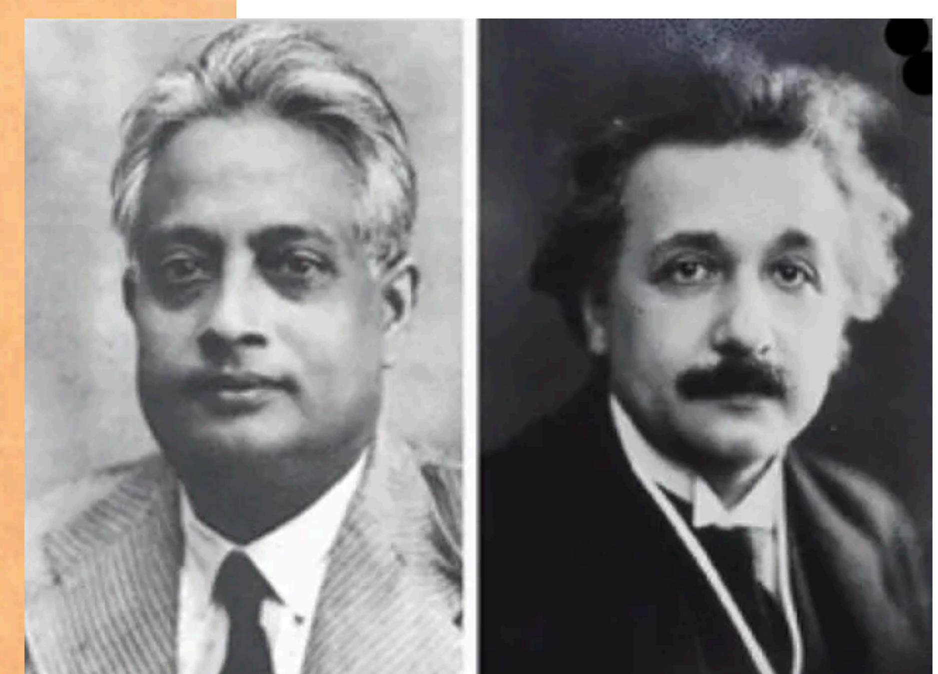
AKADEMIE DER WISSENSCHAFTEN.

Sitzung der physikalisch-mathematischen Klasse vom 8. Januar.

Quantentheorie des einatomigen idealen Gases.

Zweite Abhandlung.

Von A. Einstein.



Bose-Einstein condensate

High Temperature T:

thermal velocity v

density d^{-3}

"Billiard balls"

Low Temperature T:

De Broglie wavelength

$\lambda_{dB} = h/mv \propto T^{-1/2}$

"Wave packets"

$T = T_{crit}$: Bose-Einstein Condensation

$\lambda_{dB} \approx d$

"Matter wave overlap"

T=0: Pure Bose condensate

"Giant matter wave"

$$n^{1/3}\lambda_{dB} \sim 1$$

Bose & Fermi statistics

Two different class of particles

Under the exchange operator $x_1 \leftrightarrow x_2$ $\quad P = \pm I$

Bosons $\quad \Psi(x_1, x_2) = \Psi(x_2, x_1)$

Fermions $\quad \Psi(x_1, x_2) = -\Psi(x_2, x_1)$

Pauli's blocking

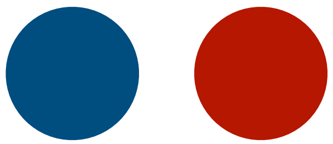
Two identical fermions cannot be the same quantum state

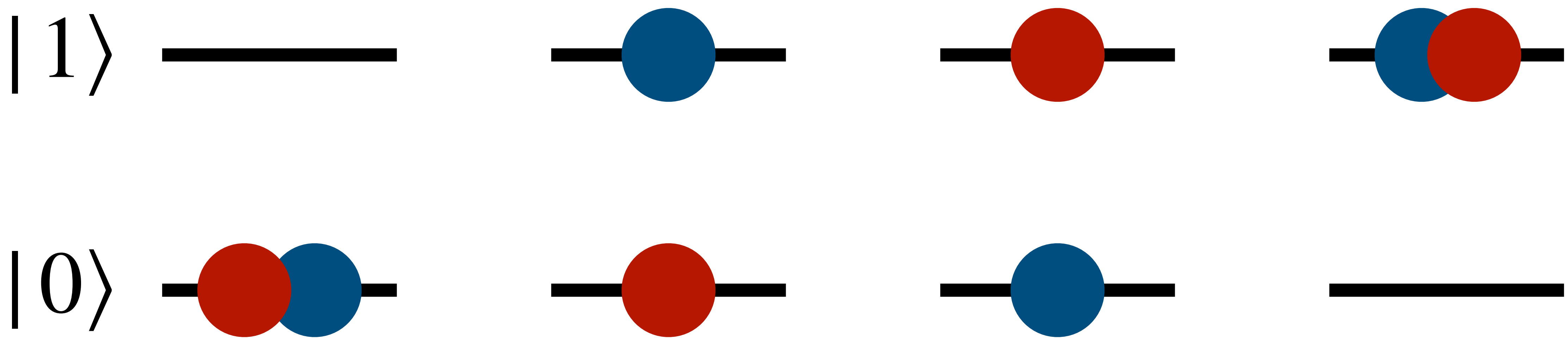
Quantum statistics

Counting number of possible configurations

Two particles in a two-level system

If two particles are different (distinguishable) particles



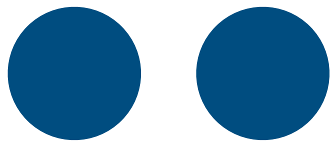


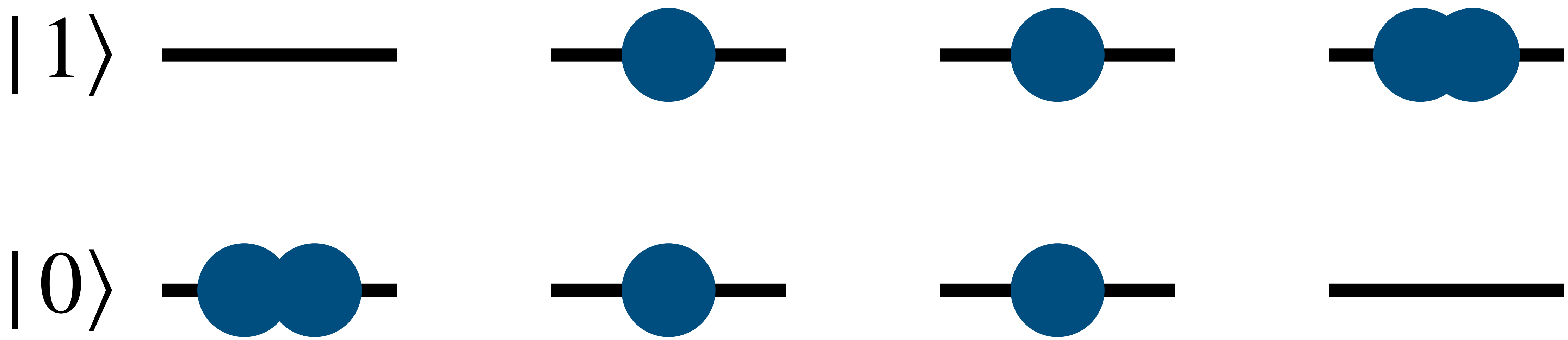
$$\Omega = 4$$

Quantum statistics

Counting number of possible configurations

Two particles in a two-level system

If two particles are different (distinguishable) particles 



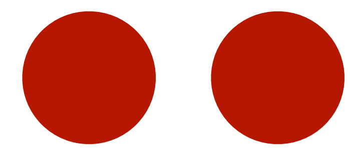
For bosons, $\Omega = 3$

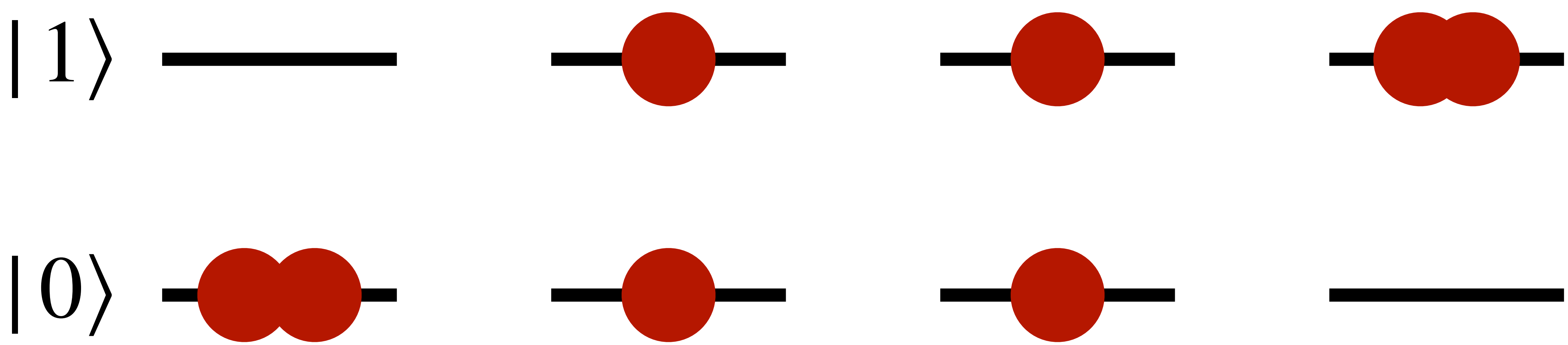
What if the particles are identical particles?

Quantum statistics

Counting number of possible configurations

Two particles in a two-level system

If two particles are different (distinguishable) particles 

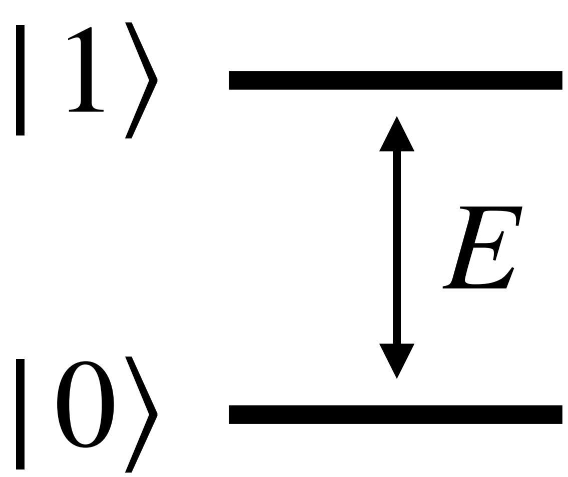


For fermions, $\Omega = 1$

What if the particles are identical particles?

Counting number of possible configurations

N-particles in a two-level system



Distinguishable (classical) particles

$$\Omega = 2^N$$

Identical Bose particles

$$\Omega = N + 1$$

Number of particles in the excited state

$$N_1 = \frac{p}{p+1} N$$

$$p = e^{-E/k_B T}$$

$$N_1 = \frac{p}{1-p} - \frac{(N+1)p^{N+1}}{1-p^{N+1}}$$

$$N \to \infty$$

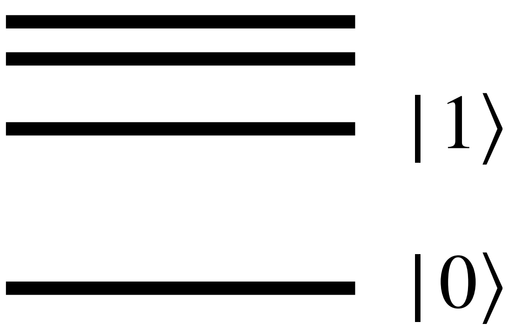
$$N_1/N \to 0!!$$

The excited state occupation is **saturated**

Bose-Einstein condensation

Counting number of possible configurations

N-particles in a infinite-level system



$$N_e = \int d\epsilon \frac{g(\epsilon)}{e^{\beta(\epsilon-\mu)} - 1}$$

$g(\epsilon) \propto \epsilon^{1/2}$

$$= \frac{V}{\lambda_{dB}^3}\zeta(1.5) \longrightarrow n_c\lambda_{dB}^3 \simeq 2.612$$

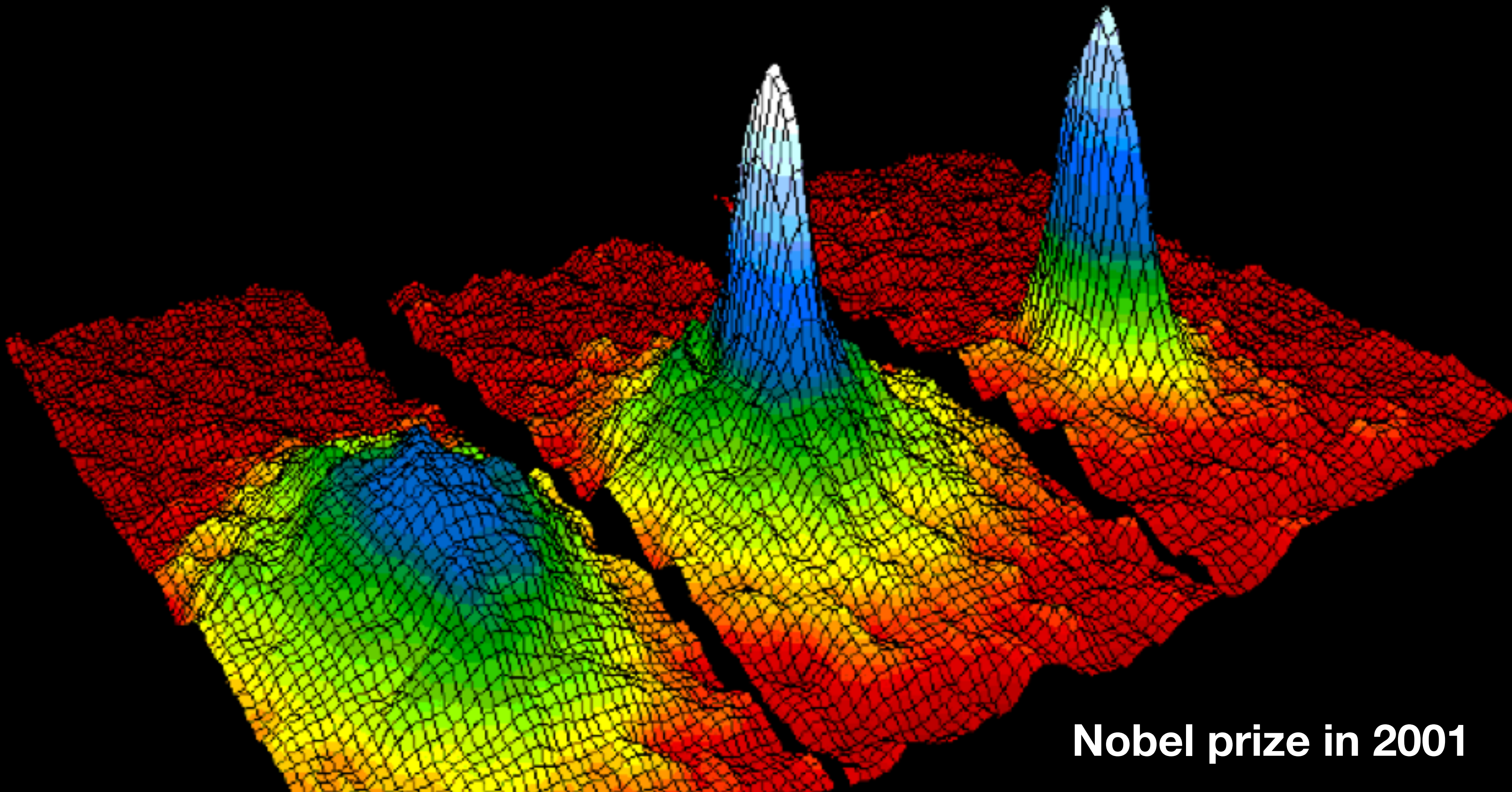
Saturation number of the excited state

Bose-Einstein condensation

When total number of particles $N > N_e$,

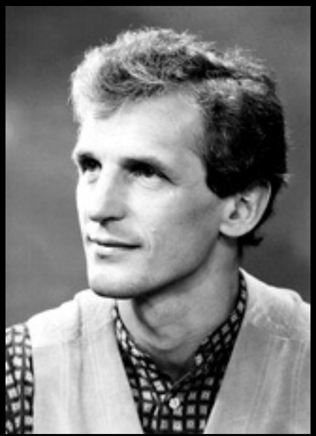
remaining particles are occupied in the ground state

The first Bose-Einstein condensation of Rubidium-87 atoms (1995)



Nobel prize in 2001

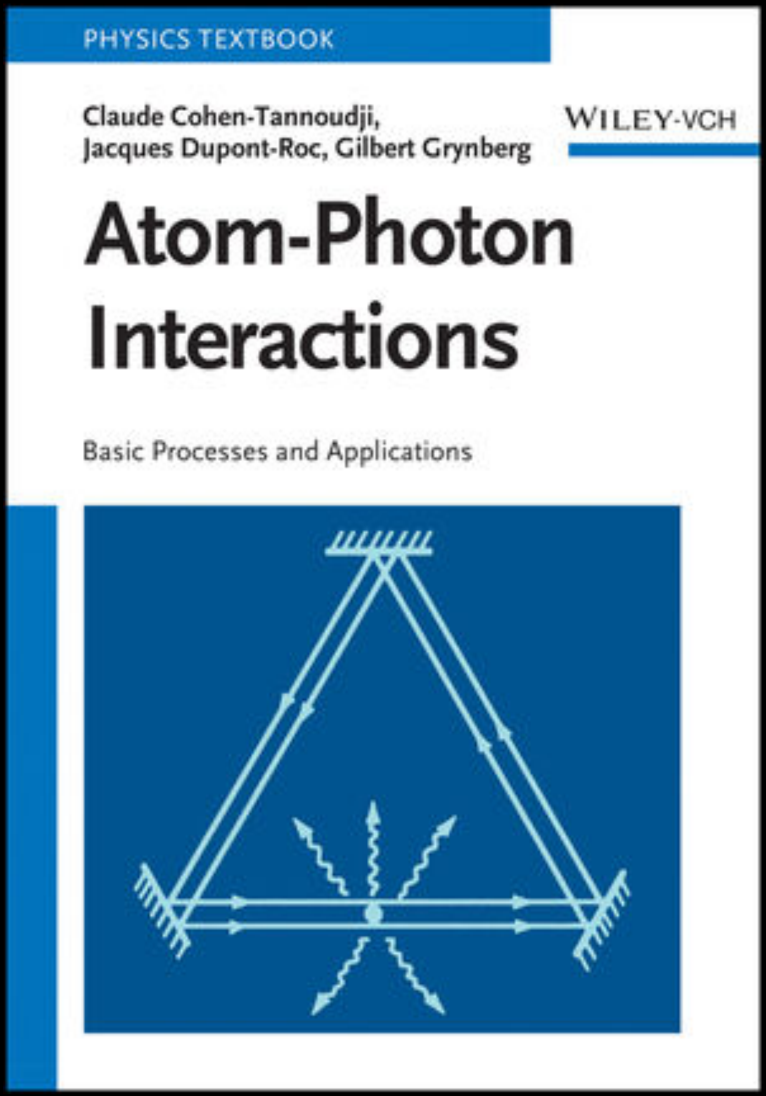
Eric A. Cornell



Wolfgang Ketterle

Carl.E. Wieman

Atom-photon interactions



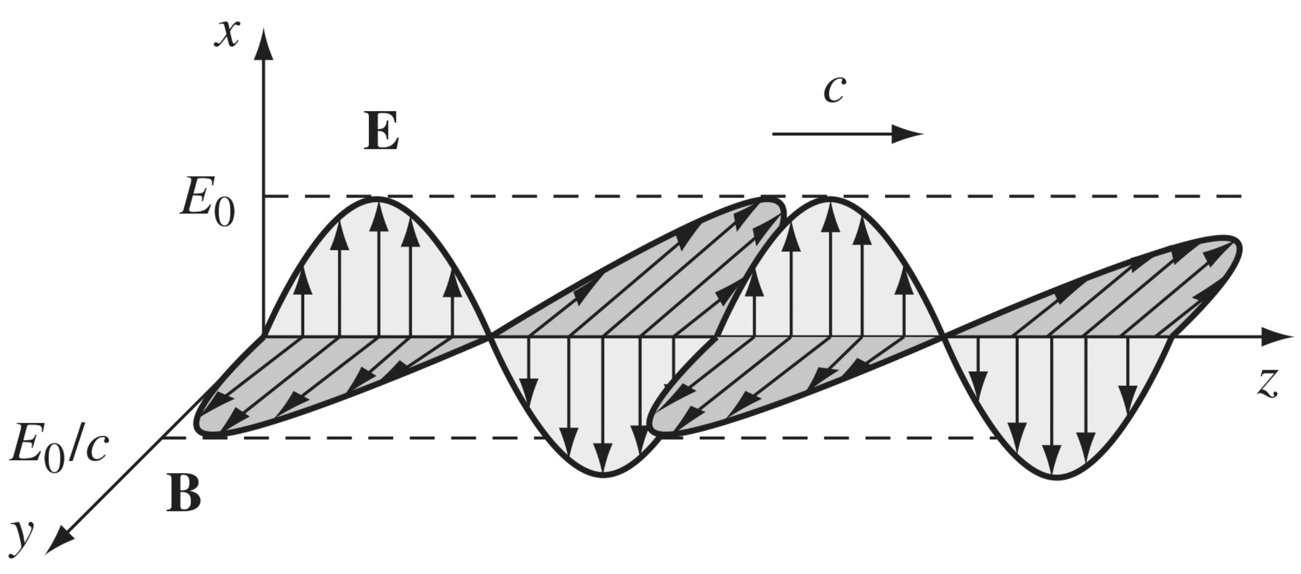
Electromagnetic wave propagating in a vacuum

(i) $\nabla \cdot \mathbf{E} = \frac{1}{\epsilon_0}\rho = 0$	(Gauss's law)
(ii) $\nabla \cdot \mathbf{B} = 0$	(no name)
(iii) $\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$	(Faraday's law)
(iv) $\nabla \times \mathbf{B} = \mu_0\epsilon_0 \frac{\partial \mathbf{E}}{\partial t}$	(Ampère's law with Maxwell's correction)

$$\nabla^2 \mathbf{E} = \mu_0\epsilon_0 \frac{\partial^2 \mathbf{E}}{\partial t^2}$$

$$\nabla^2 \mathbf{B} = \mu_0\epsilon_0 \frac{\partial^2 \mathbf{B}}{\partial t^2} \qquad c = \frac{1}{\mu_0\epsilon_0} \simeq 2.99 \times 10^8 \text{ m/s}$$

$$\frac{\partial^2 \tilde{f}}{\partial z^2} = \frac{1}{v^2}\frac{\partial^2 \tilde{f}}{\partial t^2}$$ Wave equation with velocity v



Light

is a form of energy

has momentum,

and exerts forces.

DE COMETIS LIBELLI TRES.

I. *ASTRONOMICVS, Theoremata continens de motu Cometarum, vbi Demonstratio Apparentiarum & altitudinis Cometarum qui Annis 1607. & 1618. conspecti sunt, noua & παράδοξος.*

II. *PHYSICVS, continens Physiologiam Cometarum nouam & παράδοξον.*

III. *ASTROLOGICVS, de significationibus Cometarum Annorum 1607. & 1618.*

AVTORE

IOHANNE KEPLERO, SAC. CÆS. MAIEST. MAthematico,

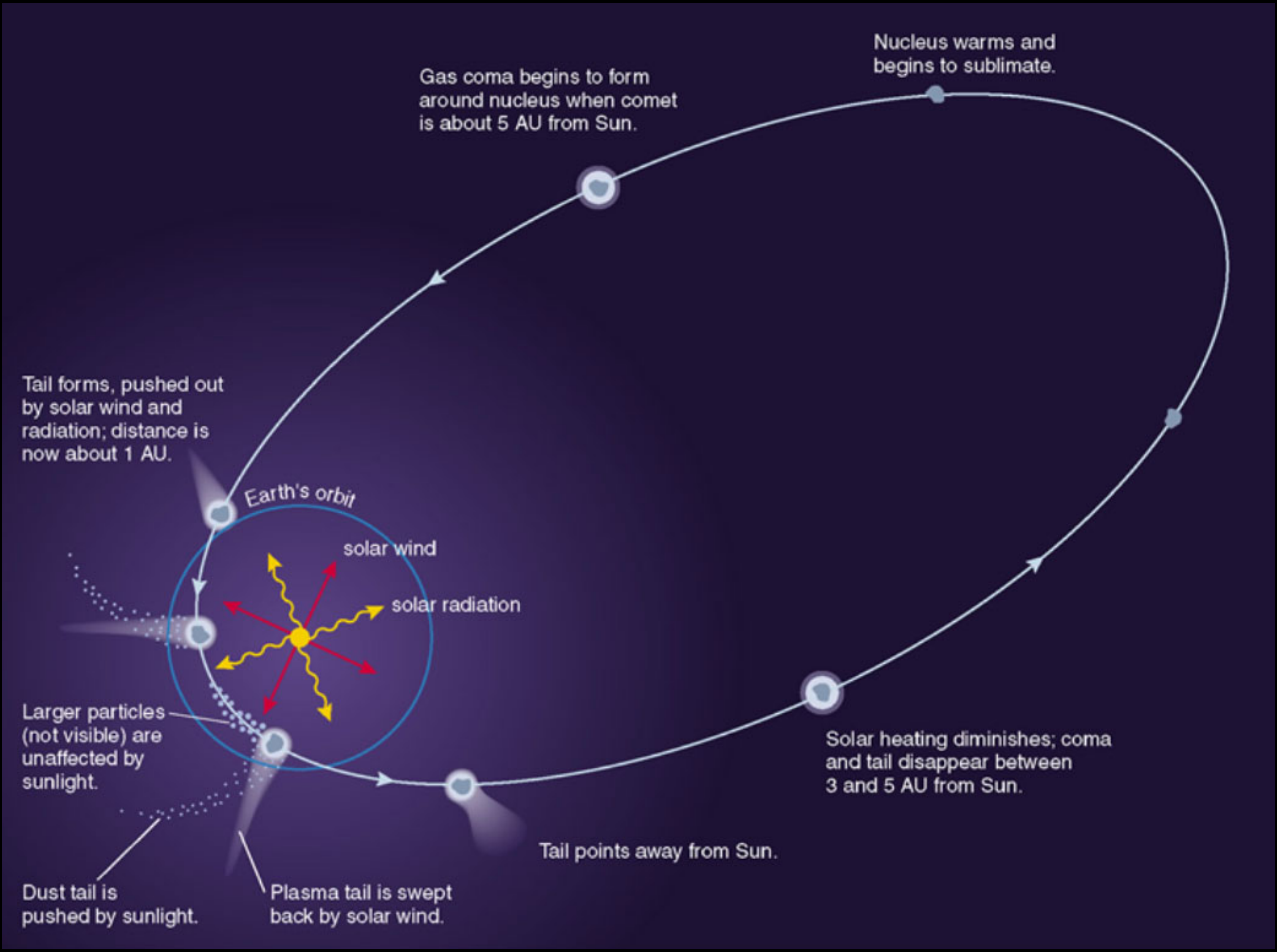
Seneca Nat. Quæst. lib. 6. cap. 26.

Erit qui demonstret aliquando, in quibus Cometæ partibus errent, cur tam seducti à cæteris eant, quanti qualesq; sint. Contenti simus inuentis: aliquid veritati & posteri conferant.

Cum Priuilegio Sac. Cæsareæ Maiest. ad Annos XV.

AVGVSTÆ VINDELICORVM,

Typis Andreæ Apergeri, Sumptibus Sebastiani Mylii Bibliopolæ Augustani, M. DC. XIX.



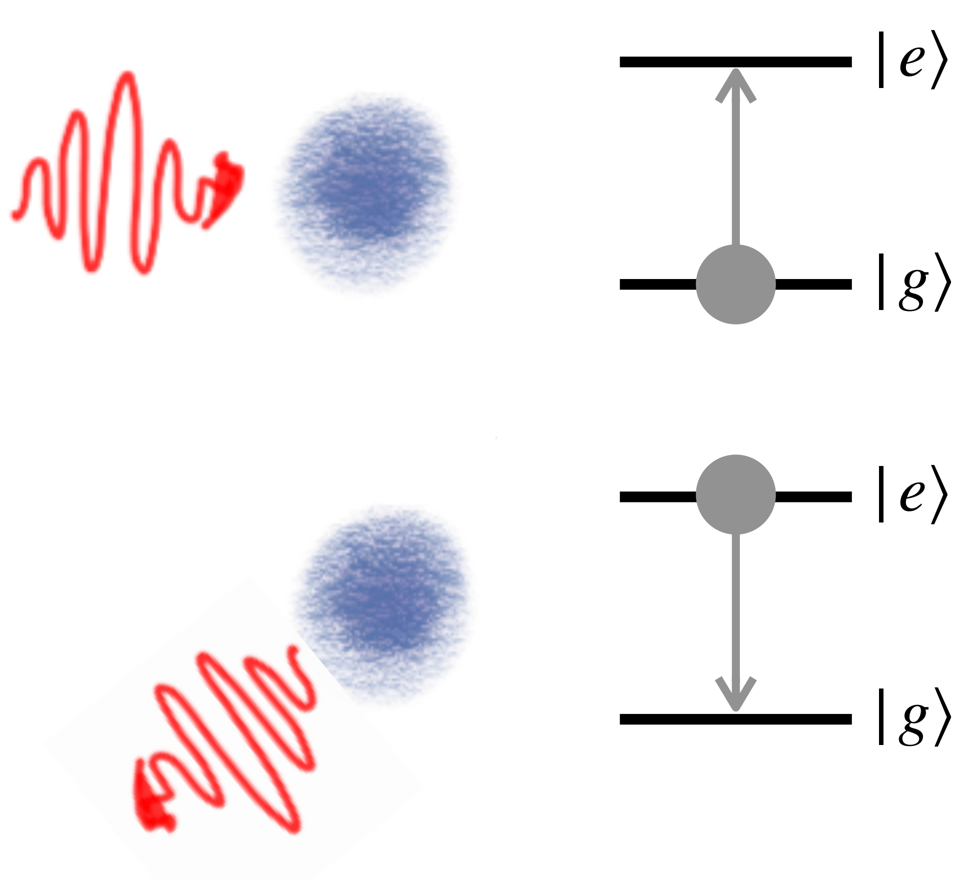
Nucleus warms and begins to sublimate.
Gas coma begins to form around nucleus when comet is about 5 AU from Sun.
Tail forms, pushed out by solar wind and radiation; distance is now about 1 AU.
Earth's orbit
solar wind
solar radiation
Larger particles (not visible) are unaffected by sunlight.
Solar heating diminishes; coma and tail disappear between 3 and 5 AU from Sun.
Tail points away from Sun.
Dust tail is pushed by sunlight.
Plasma tail is swept back by solar wind.

How can the light exert a force on a neutral atom?

$$\mathbf{F} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B})$$

Dissipative force

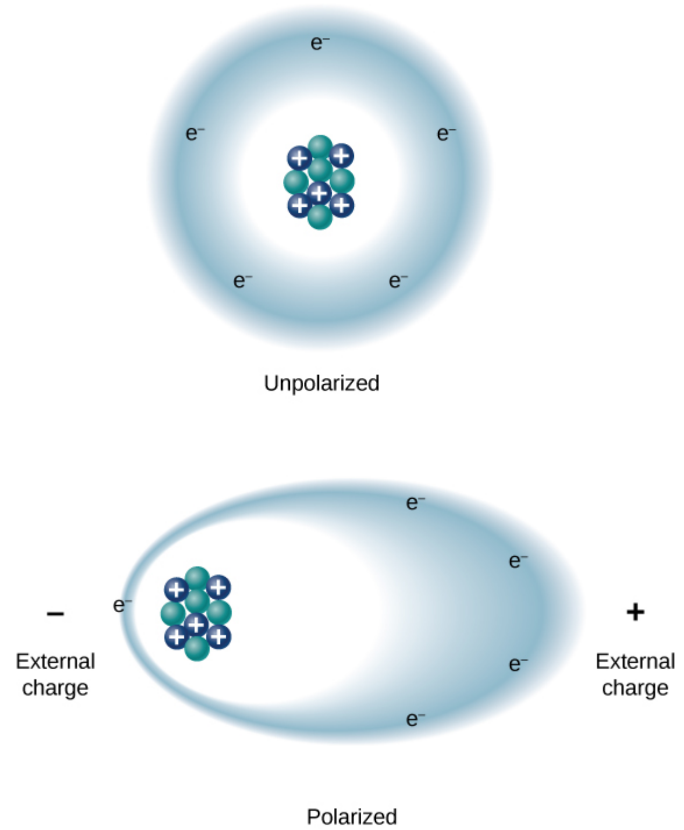
(1) Near-resonant light interaction



(absorption & emission)

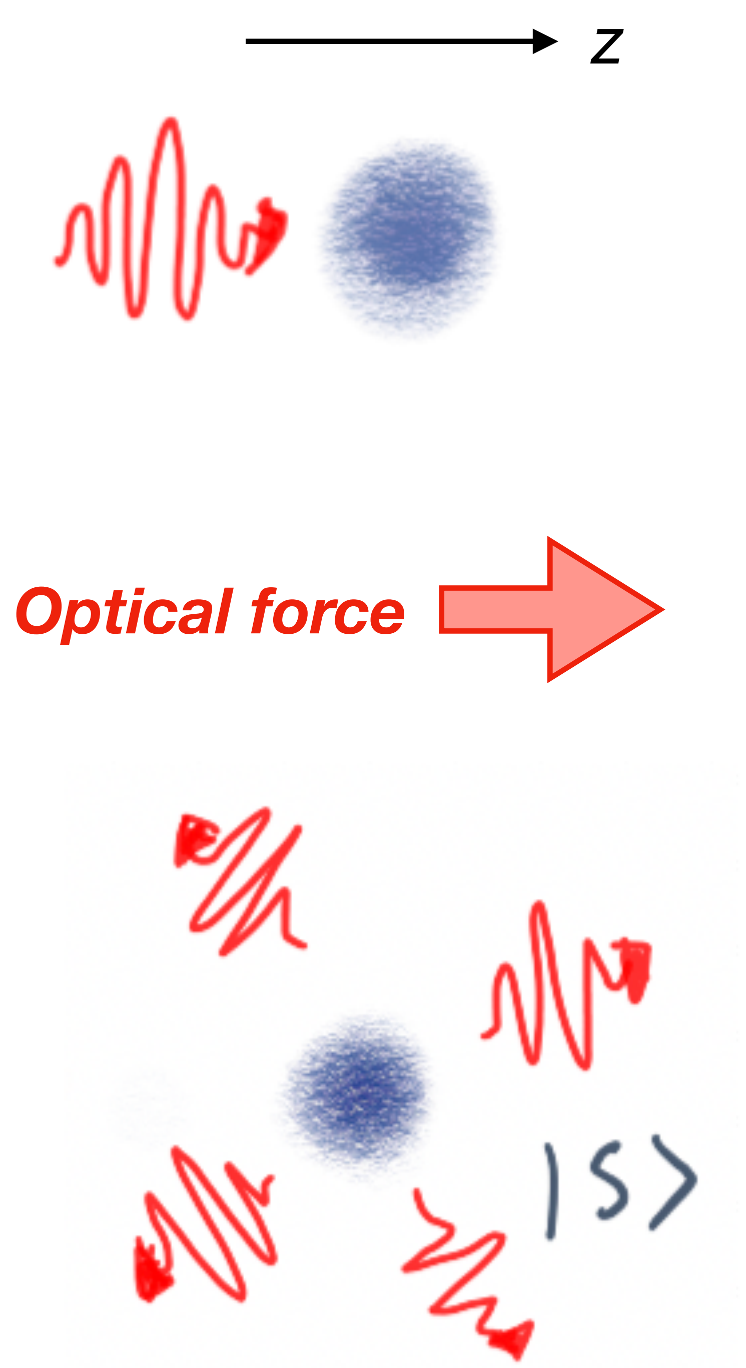
Conservative force

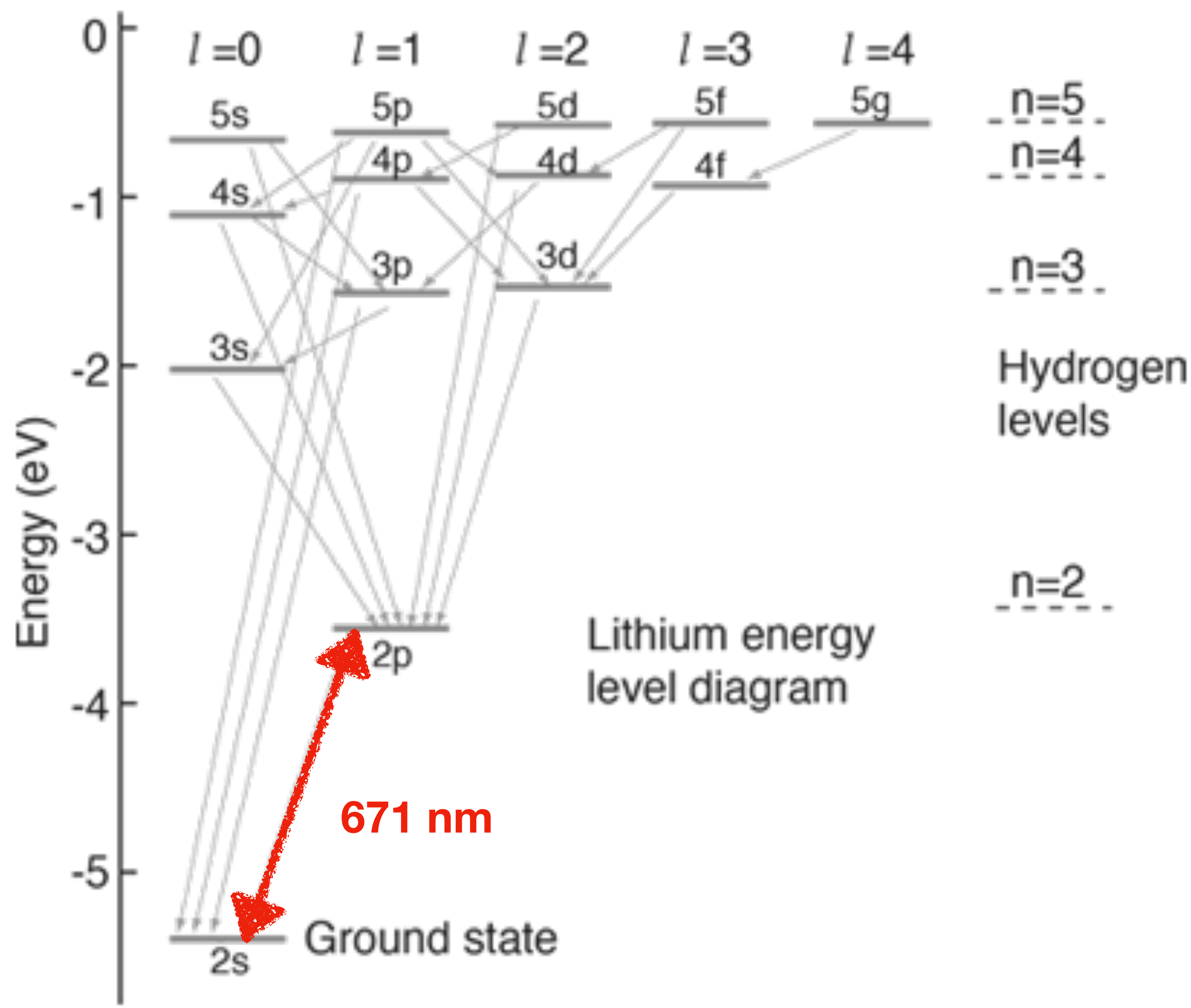
(2) Off-resonant light interaction



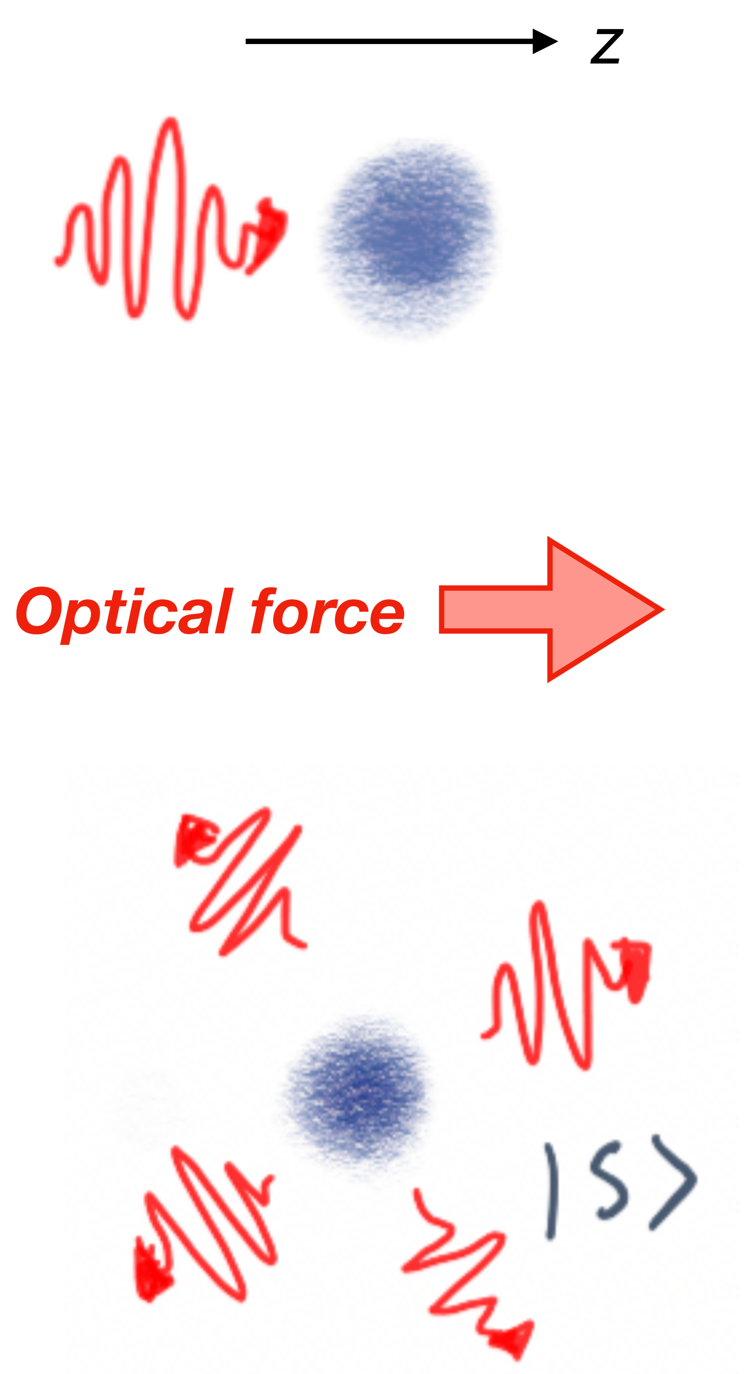
Induced dipole moment

Dissipative (radiation pressure) force





Dissipative (radiation pressure) force



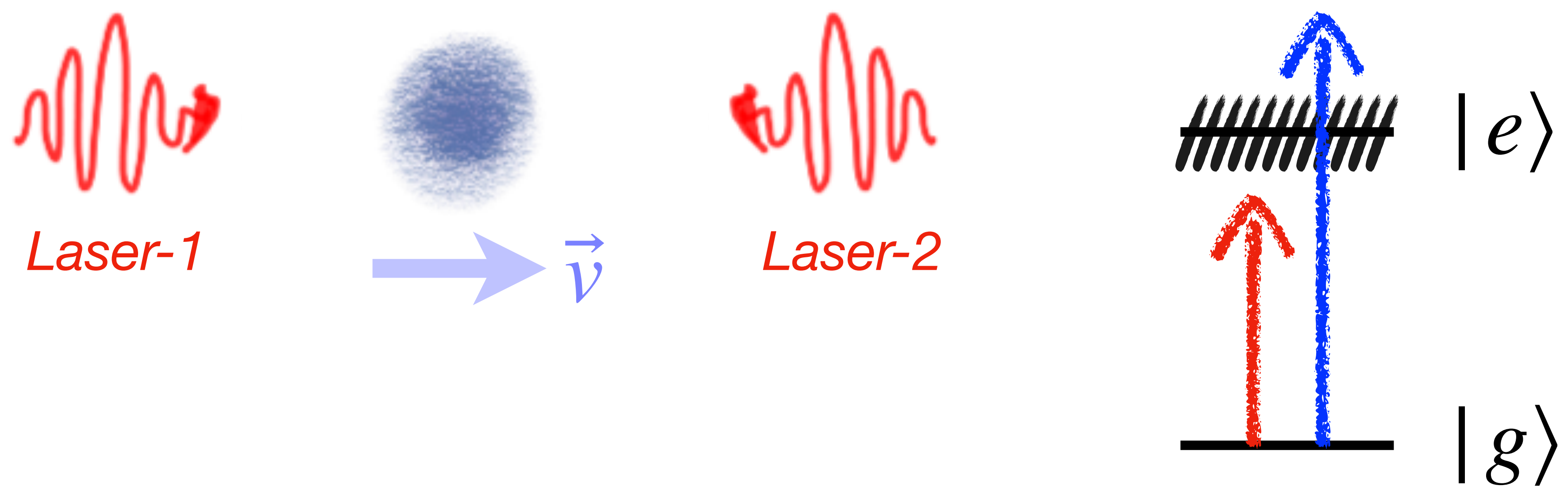
- Absorption-emission cycle transforms momentum of $\hbar k$
- It occurs on the spontaneous decay time (rate = Γ)
- Force: $\mathbf{F} = \dfrac{\Delta \mathbf{p}}{\Delta T} = \Gamma \hbar \mathbf{k}$

$$F^{\max} = \frac{\hbar k}{2}\Gamma \longrightarrow a_{\text{dec}} = \frac{F}{m} \sim 10^6 m/s^2$$

An atom moving at **1 km/s** can be stopped within **1 ms** at a distance of **50 cm**.

Application of the dissipative force: laser cooling

Slowing down atoms with near resonant light



Q: Should we apply blue-detuned or red-detuned light to slow down the atom ?

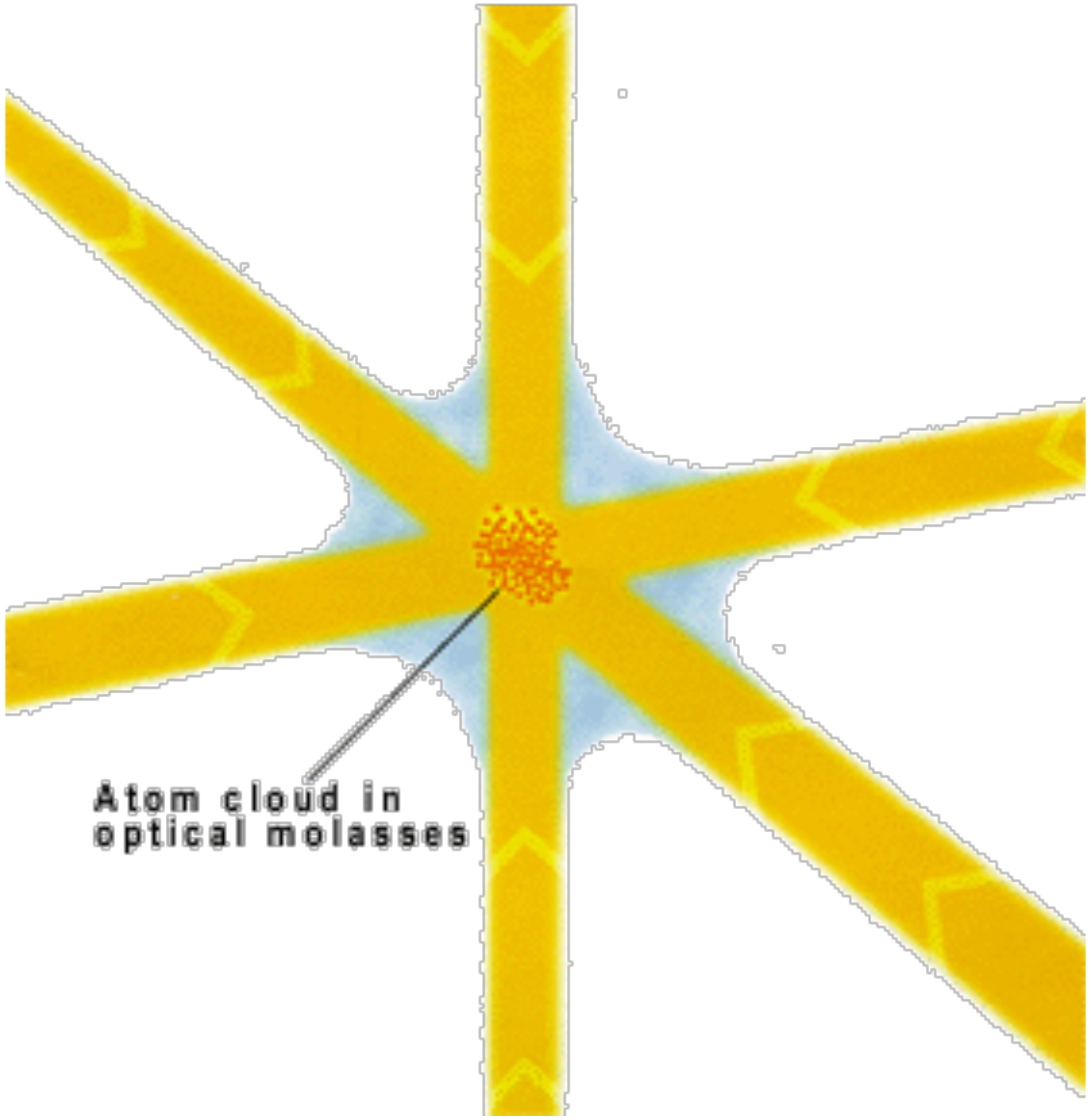
$\omega_L > \omega_0$ $\omega_L < \omega_0$

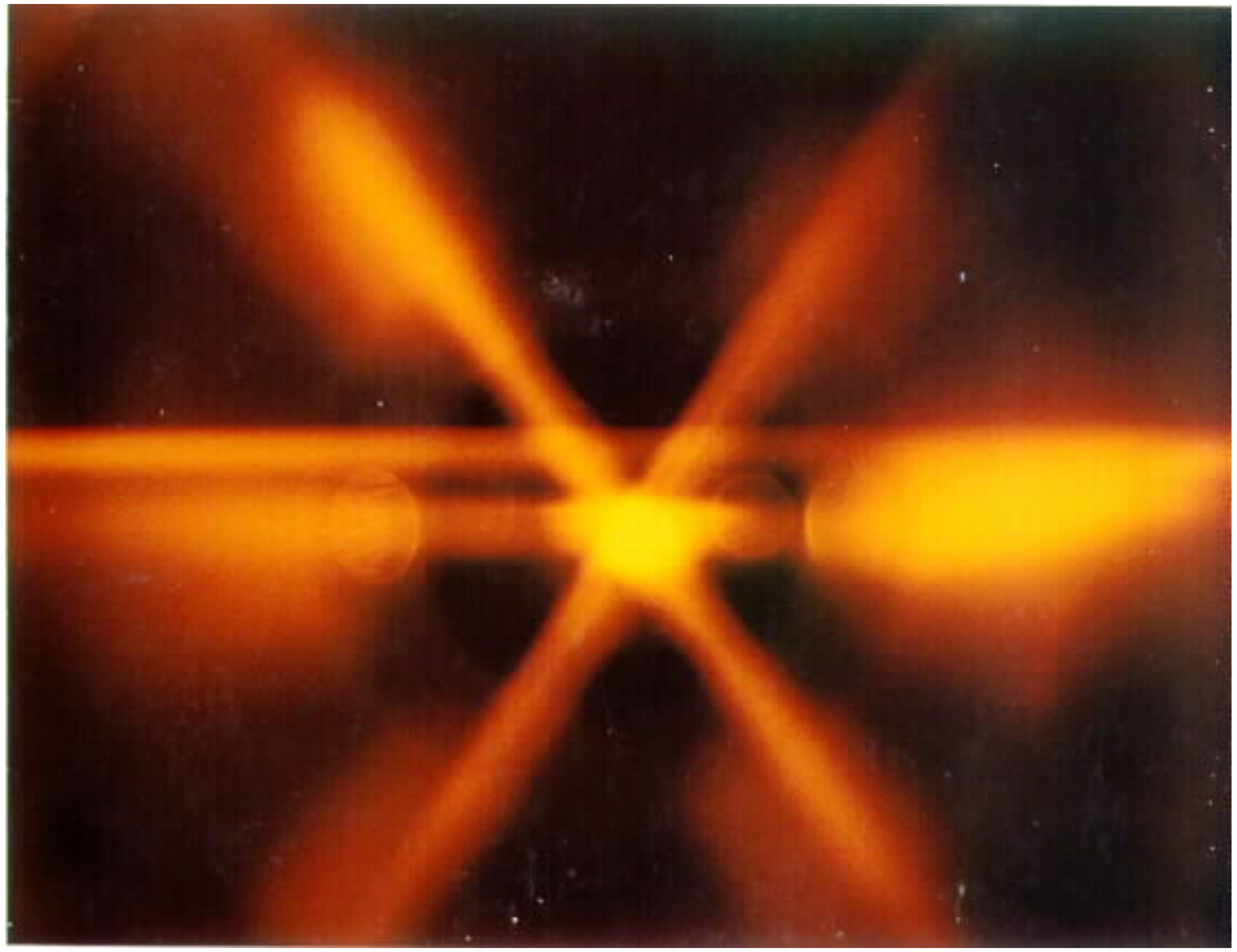
Moving atoms towards the laser see **higher** frequency

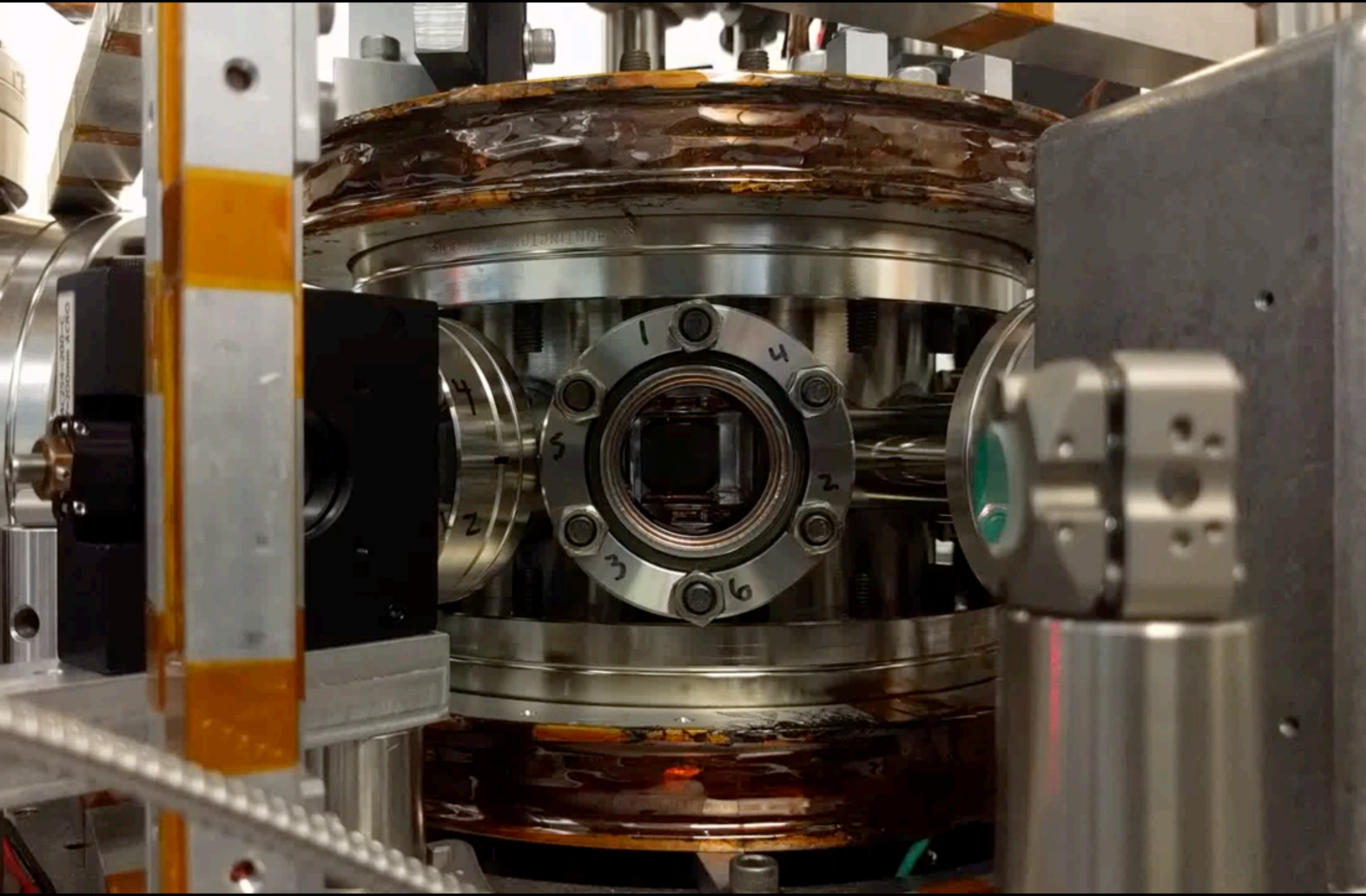
More scattering from the laser-2 than laser-1: **Red** detuned light will work

Application of the dissipative force: trapping atoms

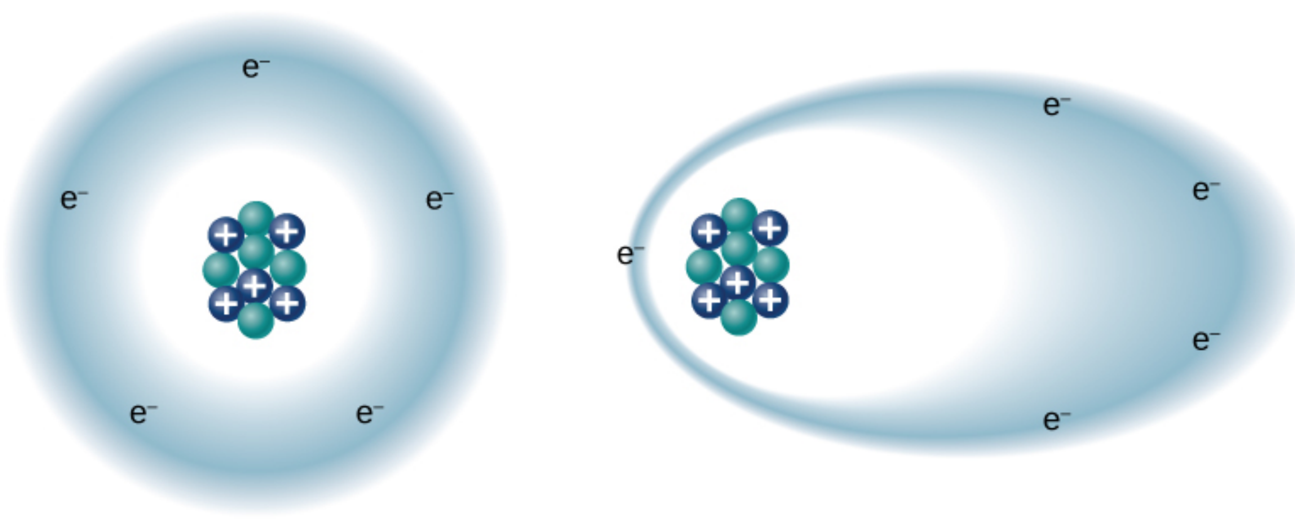
Optical molasses : applying the optical force along *x,y,z* directions





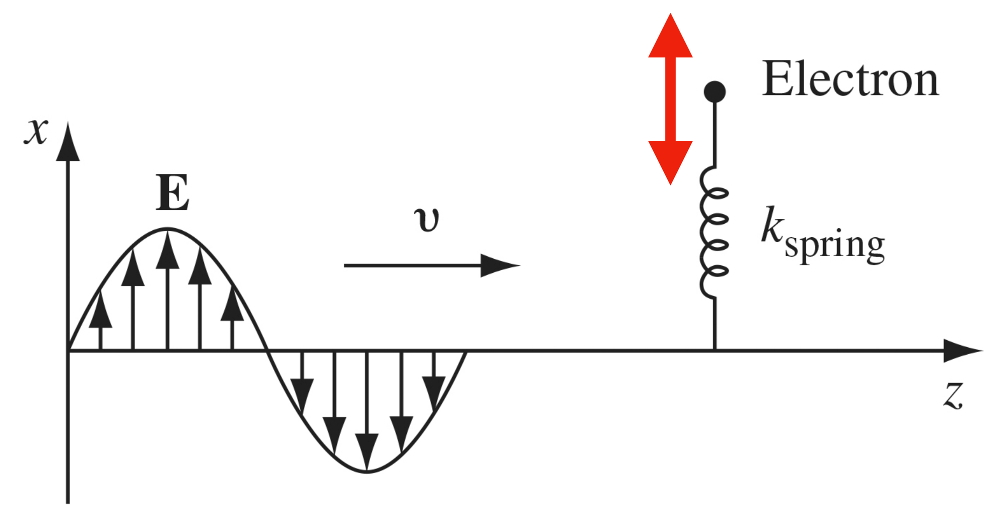


Classical model of atoms under oscillating electric field



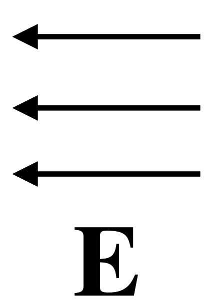
Unpolarized

Polarized



$$m\frac{d^2x}{dt^2} + m\gamma\frac{dx}{dt} + m\omega_0^2 x = qE_0 \cos \omega t$$

$$U = -\mathbf{p} \cdot \mathbf{E}$$



$\mathbf{p} // \mathbf{E}$	$(\omega < \omega_0)$
$\mathbf{p} // -\mathbf{E}$	$(\omega > \omega_0)$

Quantum mechanical treatment (perturbation theory)

$$\mu_z = -e\langle \Psi(t) | z | \Psi(t) \rangle \qquad |\Psi(t)\rangle \simeq e^{-iE_g t/\hbar}|g\rangle + \sum_{n \neq g} c_n^{(1)} e^{-iE_n t/\hbar}|n\rangle$$

$$\vec{\mu}(t) = \frac{2e^2}{\hbar}\left(\sum_{n\neq g} |\langle n|z|g\rangle|^2 \frac{\omega_{ng}}{\omega_{ng}^2 - \omega^2}\right)\mathbf{E}\cos\omega t$$

$$\Delta E = -\vec{\mu}(t)\cdot\mathbf{E}(t) \;\propto \cos^2(\omega t)$$

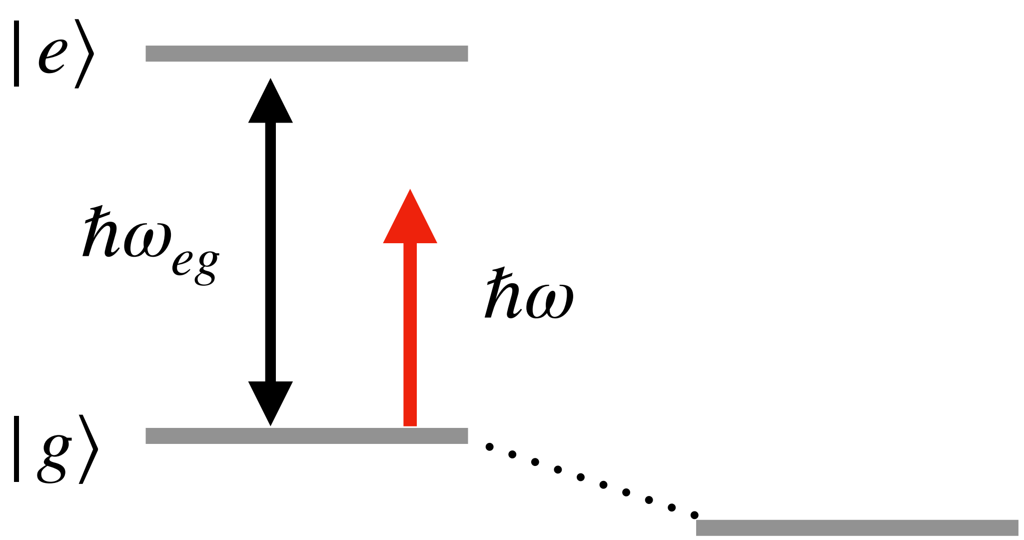
Time-averaging interaction energy becomes

$$\Delta E = -\frac{e^2|\mathbf{E}|^2}{\hbar}\sum_{n\neq g}|\langle n|z|g\rangle|^2\frac{\omega_{ng}}{\omega_{ng}^2-\omega^2}$$

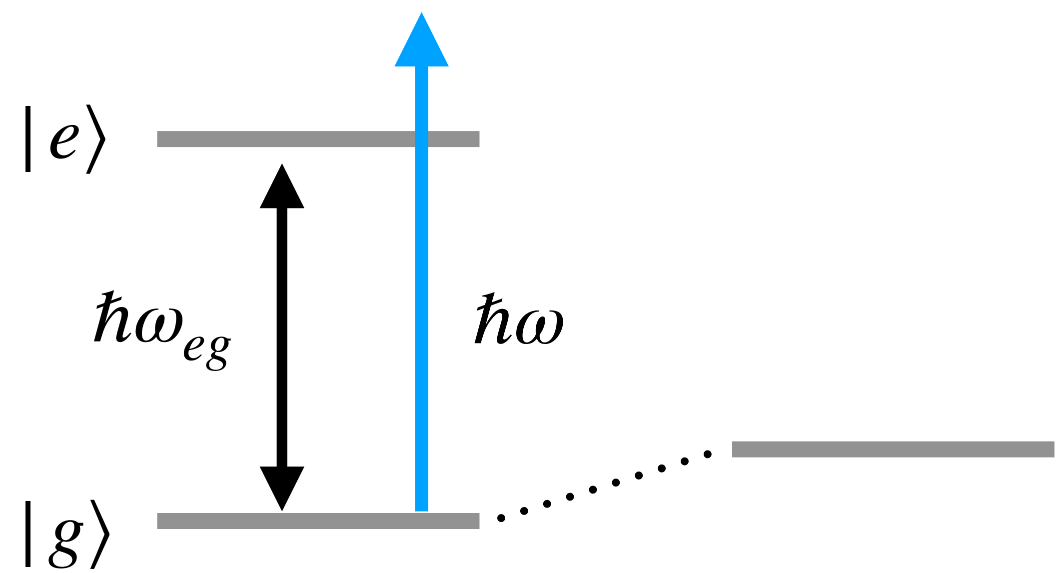
$$\Delta E \propto \frac{1}{\omega - \omega_{ng}}$$

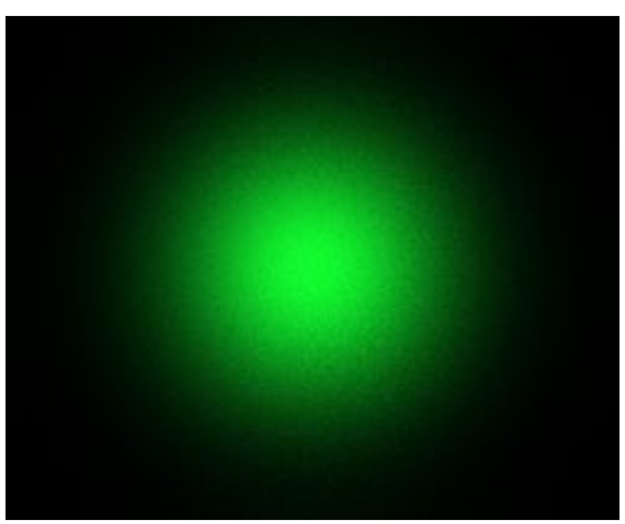
Quantum mechanical treatment (perturbation theory)

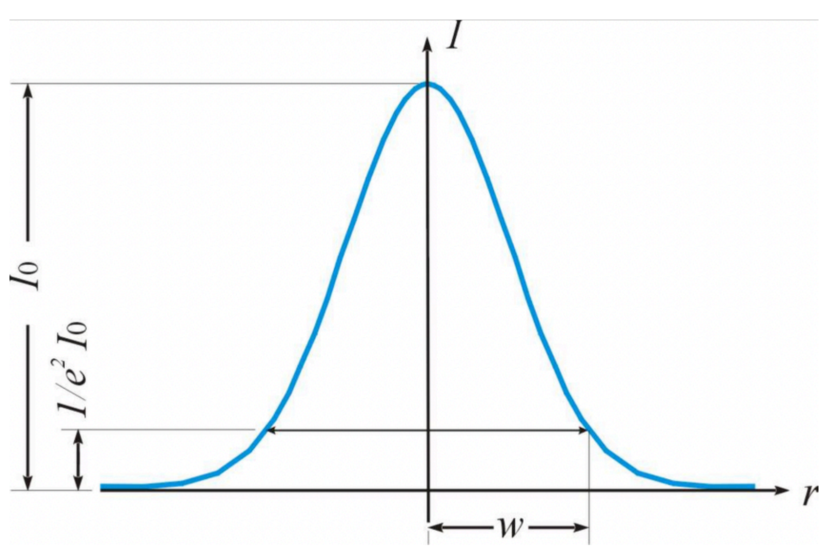
(Red-detuned laser)



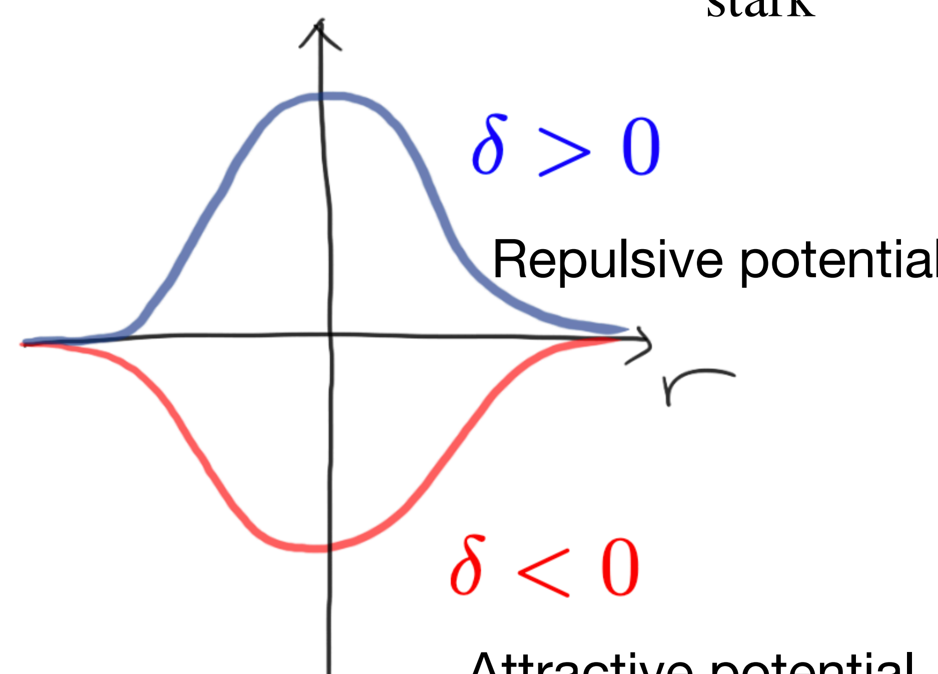
(Blue-detuned laser)





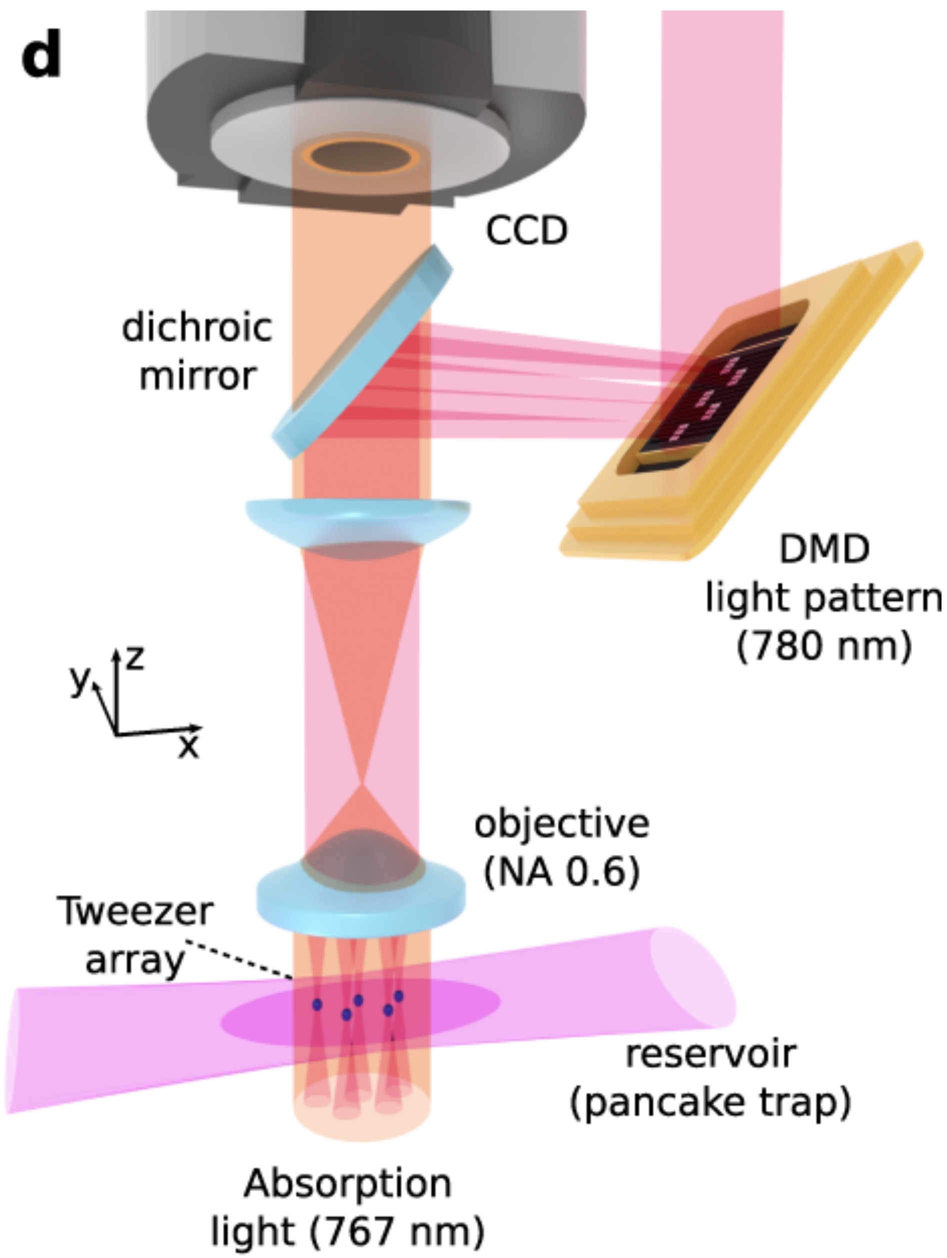


$$\mathbf{F} = -\nabla E_{\mathrm{stark}}$$



Forces on neutral atoms

Fundamental building blocks of atom-based quantum computer



Cat Video Made
with Atoms

Forces on neutral atoms

Fundamental building blocks of atom-based quantum computer

Article

A quantum processor based on coherent transport of entangled atom arrays

https://doi.org/10.1038/s41586-022-04592-6
Received: 6 December 2021
Accepted: 28 February 2022

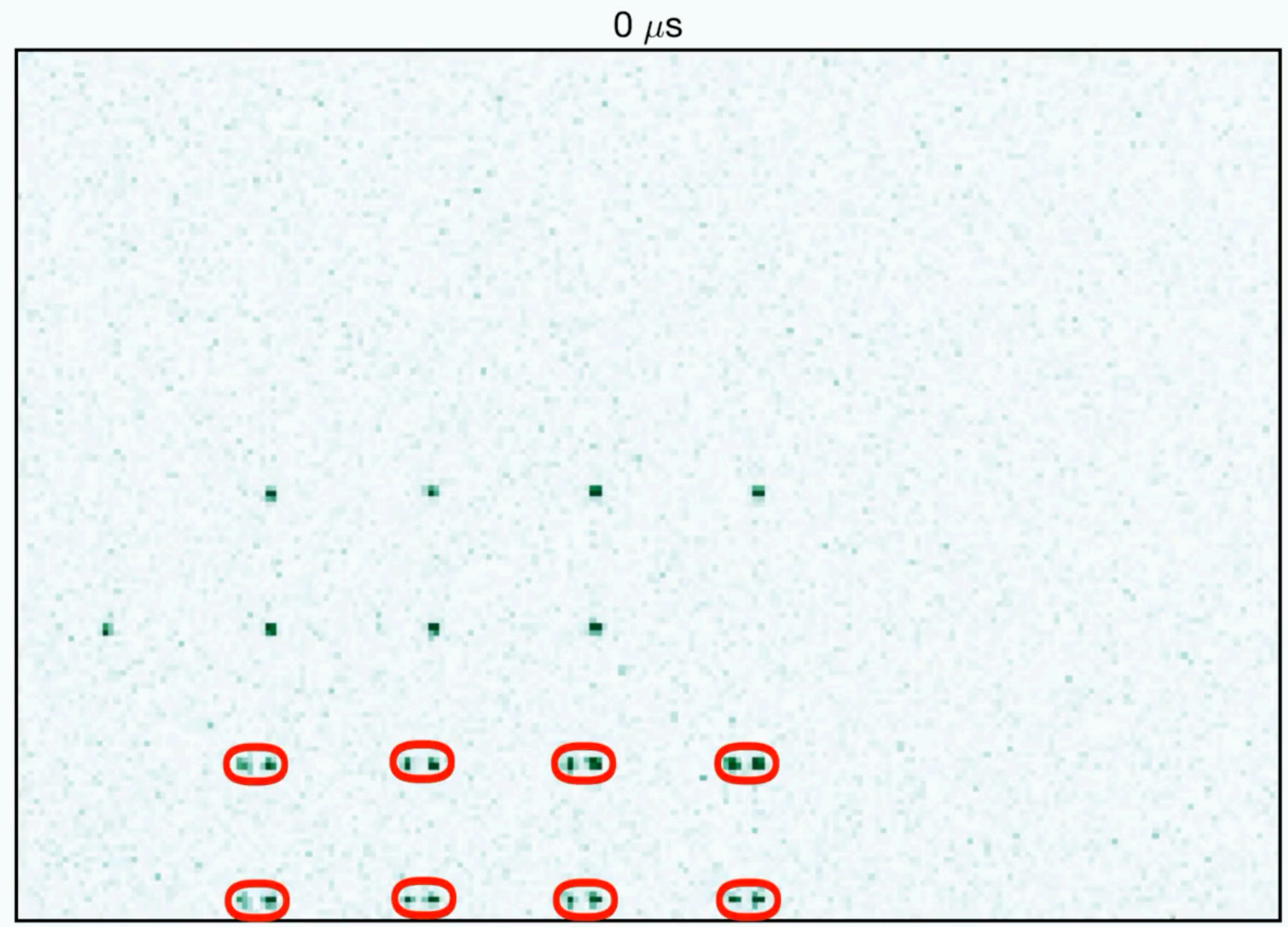
Dolev Bluvstein[1], Harry Levine[1,6], Giulia Semeghini[1], Tout T. Wang[1], Sepehr Ebadi[1], Marcin Kalinowski[1], Alexander Keesling[1,2], Nishad Maskara[1], Hannes Pichler[3,4], Markus Greiner[1], Vladan Vuletić[5] & Mikhail D. Lukin[1] ✉

Article

Logical quantum processor based on reconfigurable atom arrays

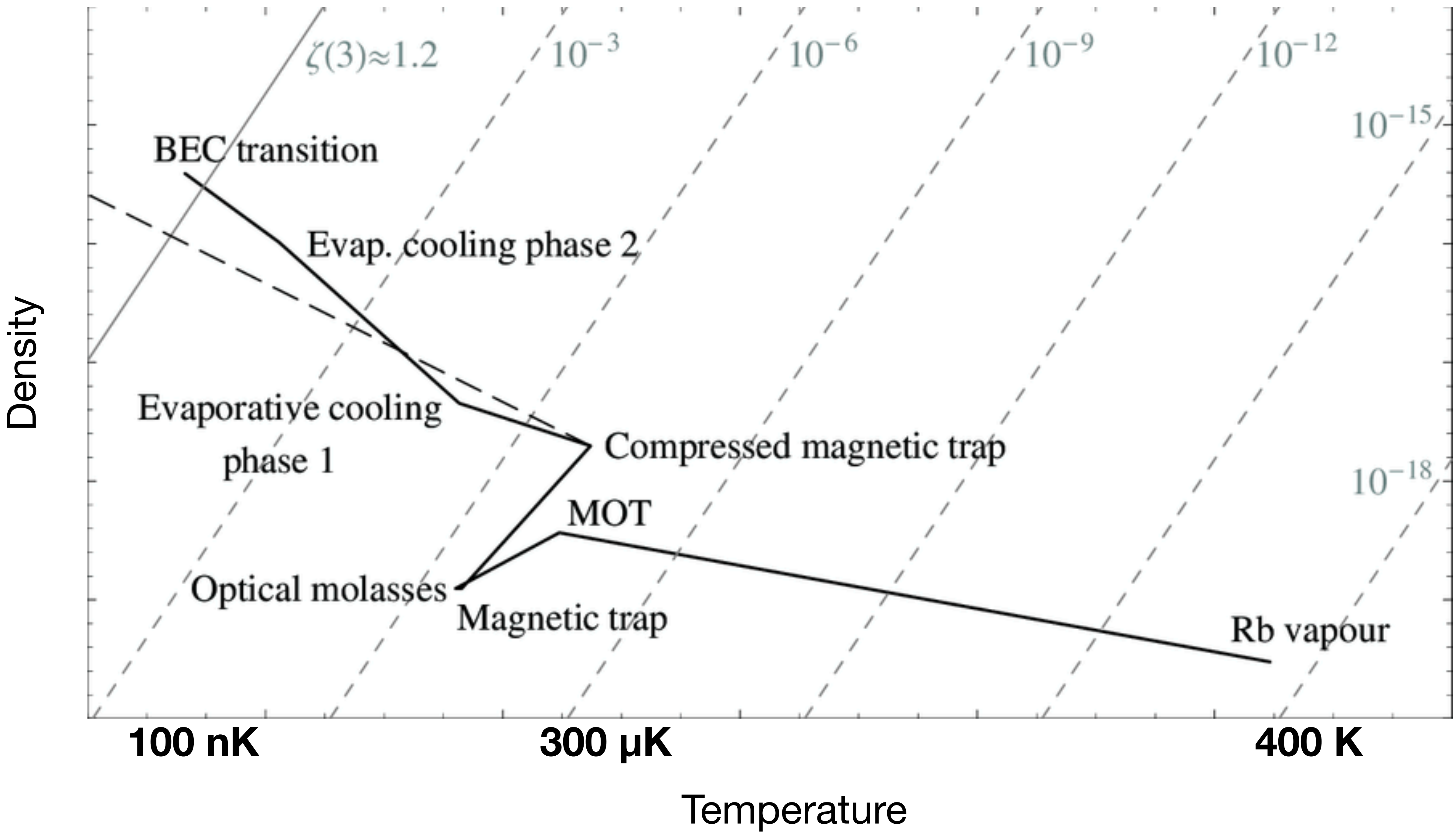
https://doi.org/10.1038/s41586-023-06927-3
Received: 21 October 2023
Accepted: 1 December 2023
Published online: 6 December 2023

Dolev Bluvstein[1], Simon J. Evered[1], Alexandra A. Geim[1], Sophie H. Li[1], Hengyun Zhou
Tom Manovitz[1], Sepehr Ebadi[1], Madelyn Cain[1], Marcin Kalinowski[1], Dominik Hangleit
J. Pablo Bonilla Ataides[1], Nishad Maskara[1], Iris Cong[1], Xun Gao[1], Pedro Sales Rodrigu
Thomas Karolyshyn[2], Giulia Semeghini[4], Michael J. Gullans[3], Markus Greiner[1], Vladan Vuletić[5] & Mikhail D. Lukin[1] ✉



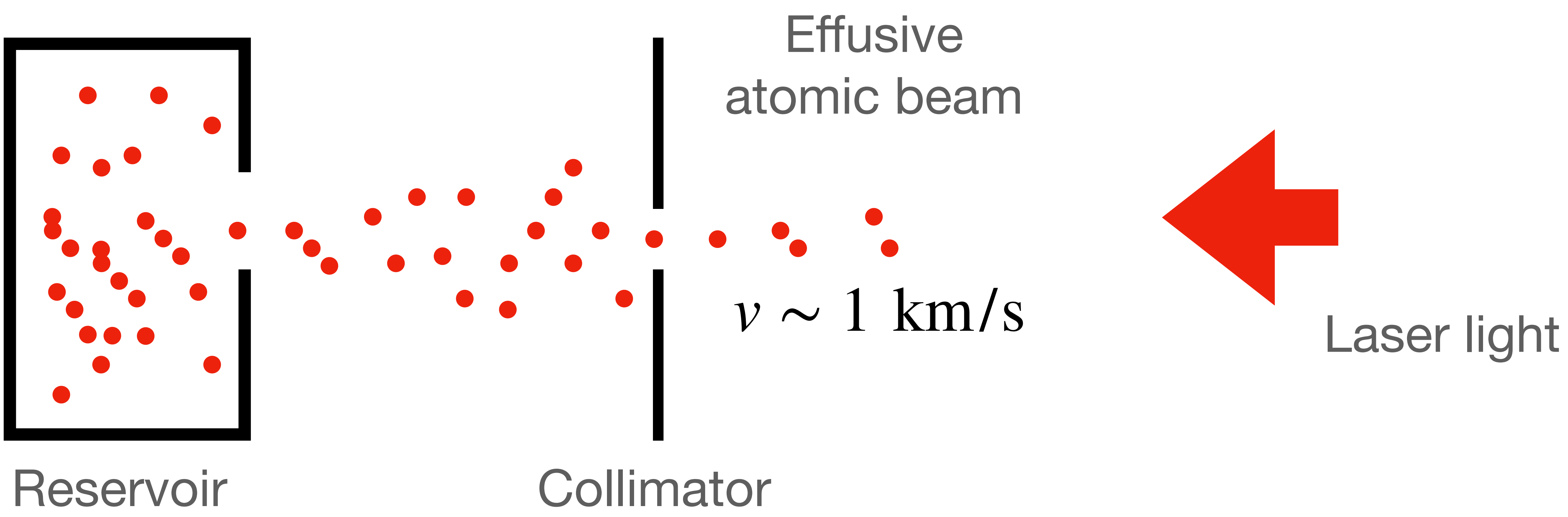
Experimental Pathway to Bose-Einstein condensation

Pathways towards the atomic BEC



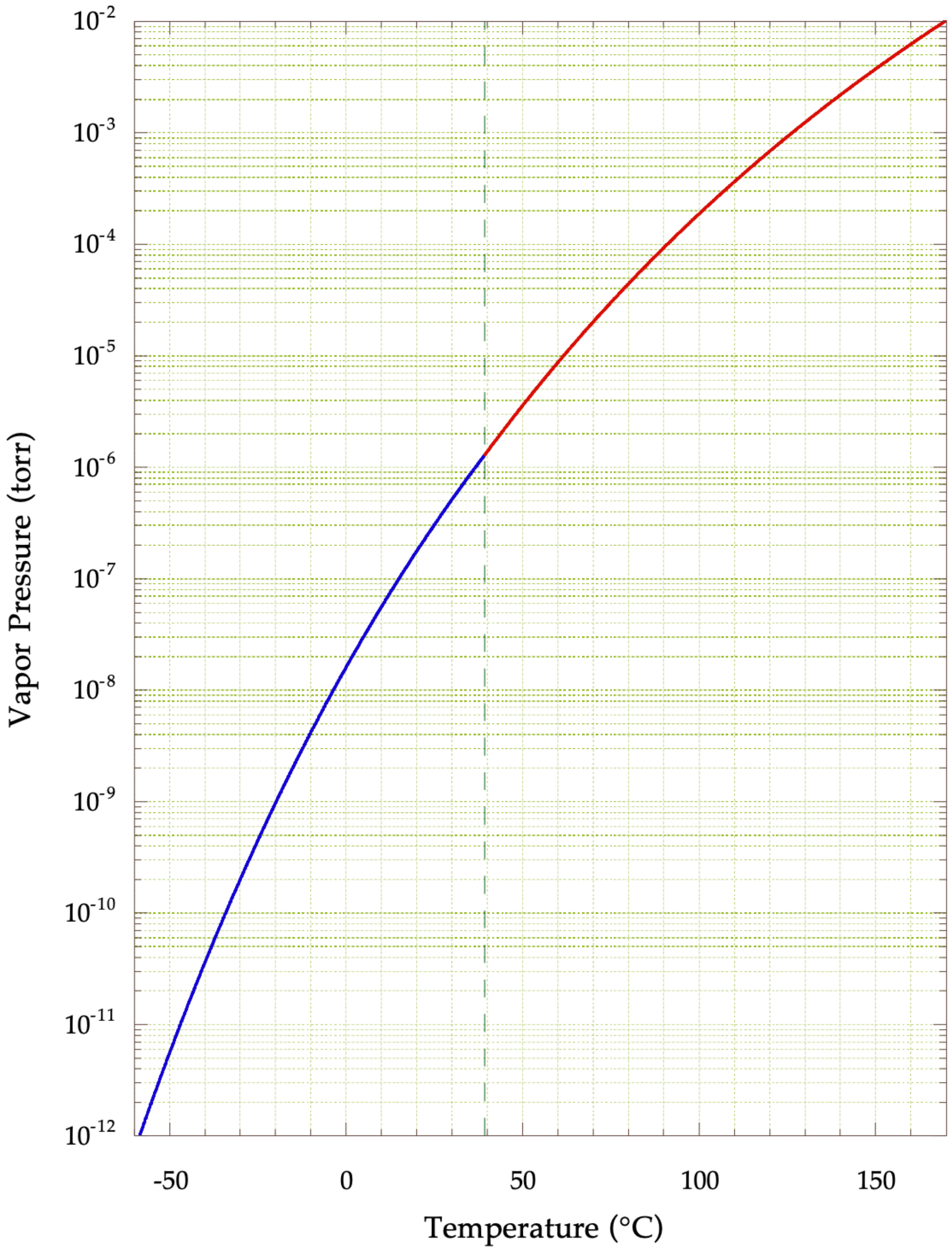
Bose-Einstein condensation

First stage: generating atomic source and slow them down

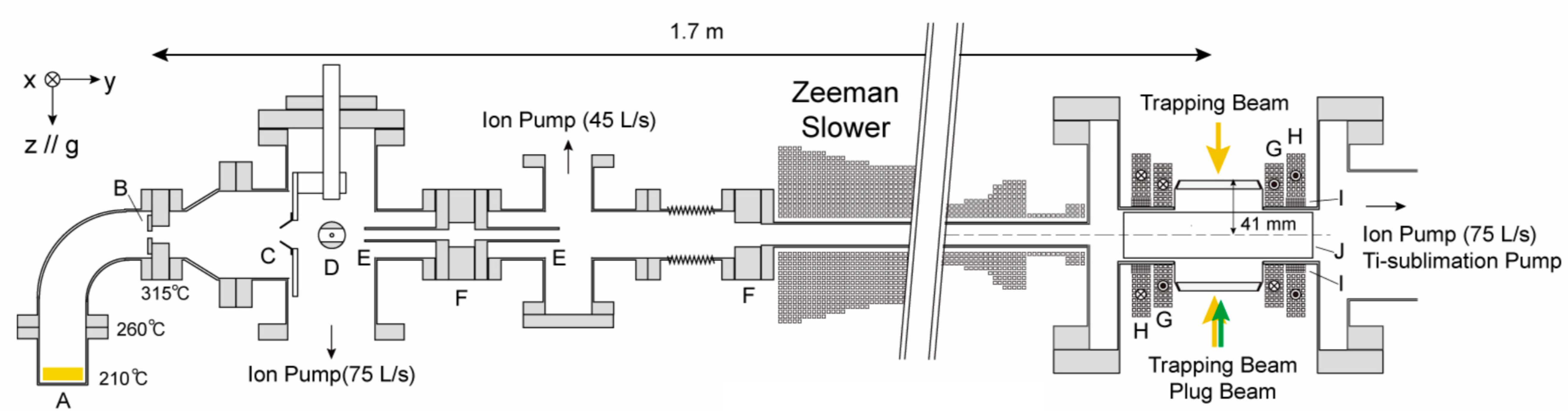


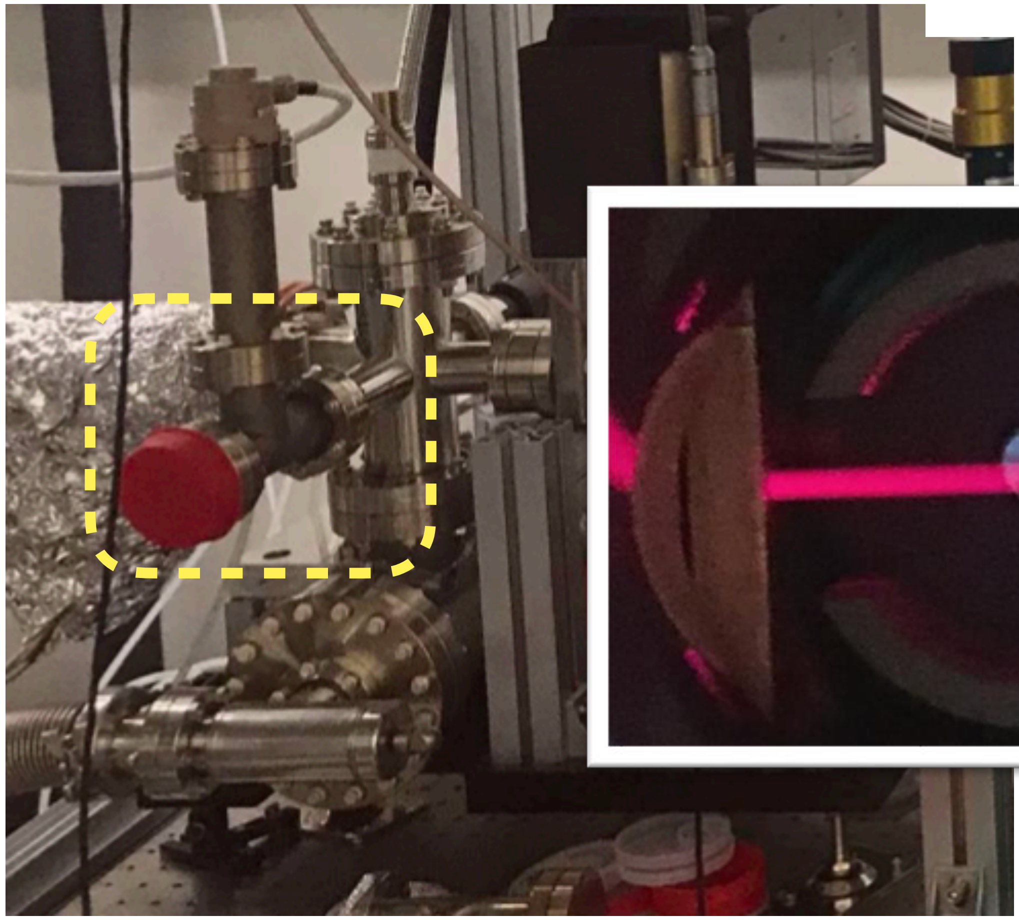
Collect high density atoms in a vacuum chamber

Boiling up the atoms from metallic state

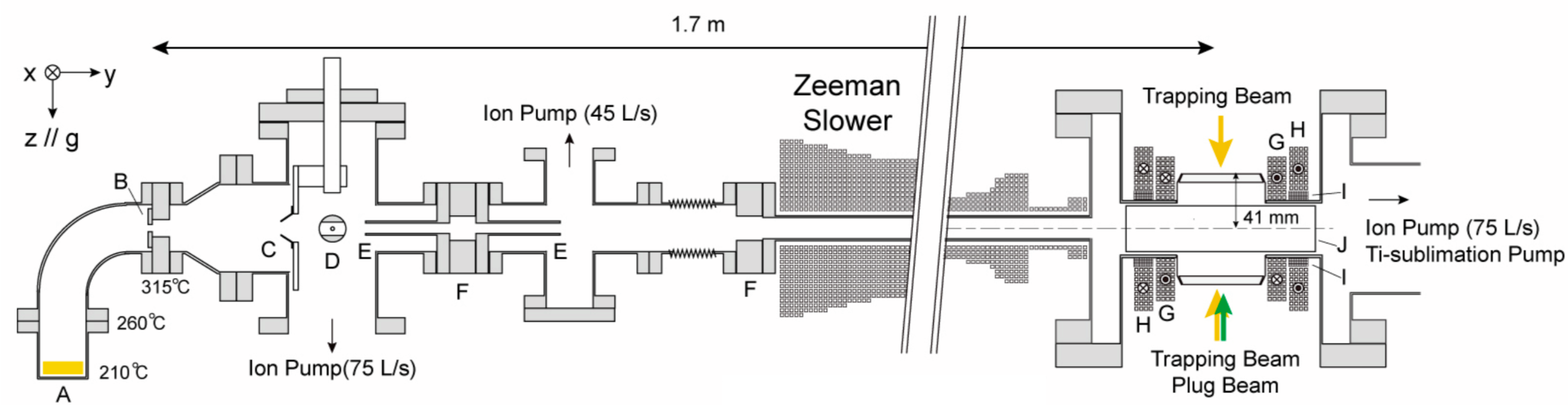


Overview of the BEC machine





Overview of the BEC machine



Step 1: Laser cooling of the atoms and trap them in the main chamber

Number of atoms: $N \sim 10^9 - 10^{10}$

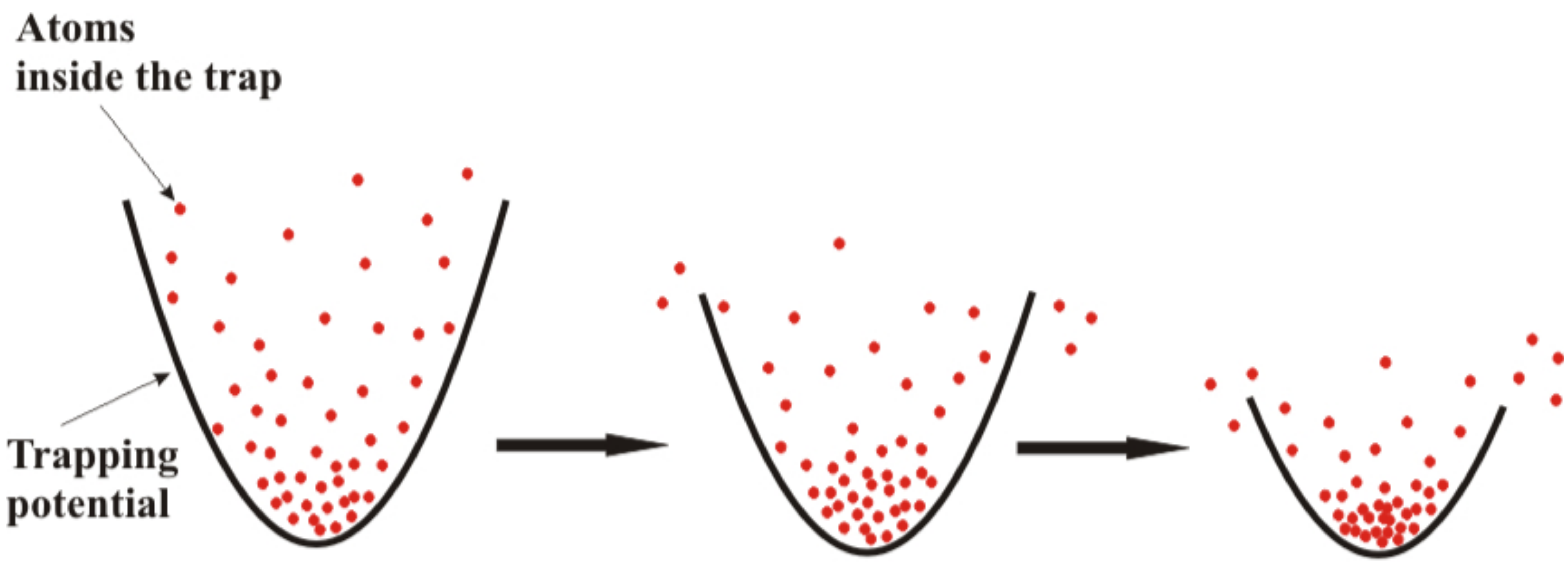
Temperature: $T \sim 300\ \mu K$

Density: $n \sim 10^{12}/cm^3$

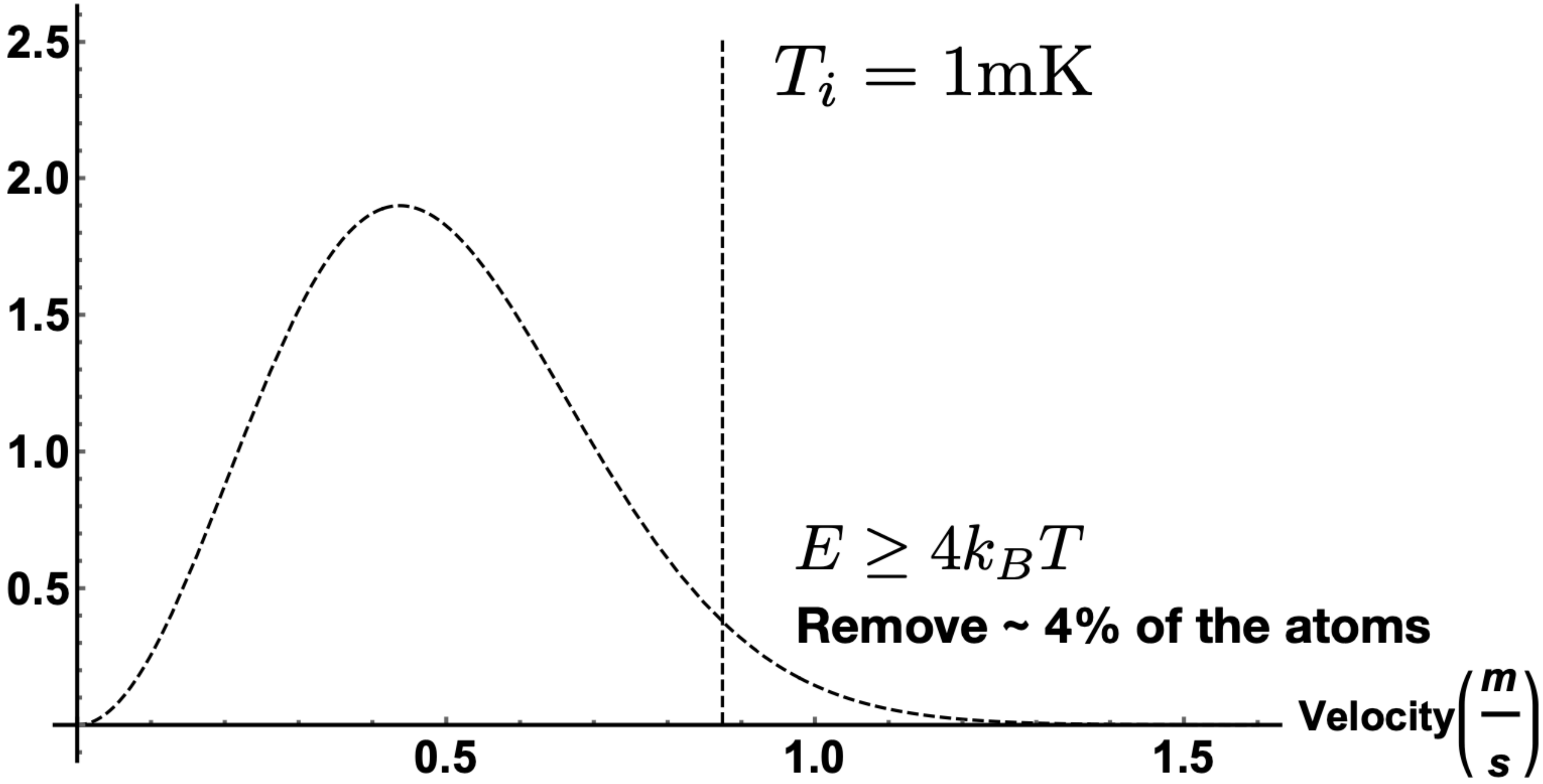
Phase spece density: $n\lambda^3 \sim 10^{-5} - 10^{-6}$

Trapping and cooling atoms in magnetic trap

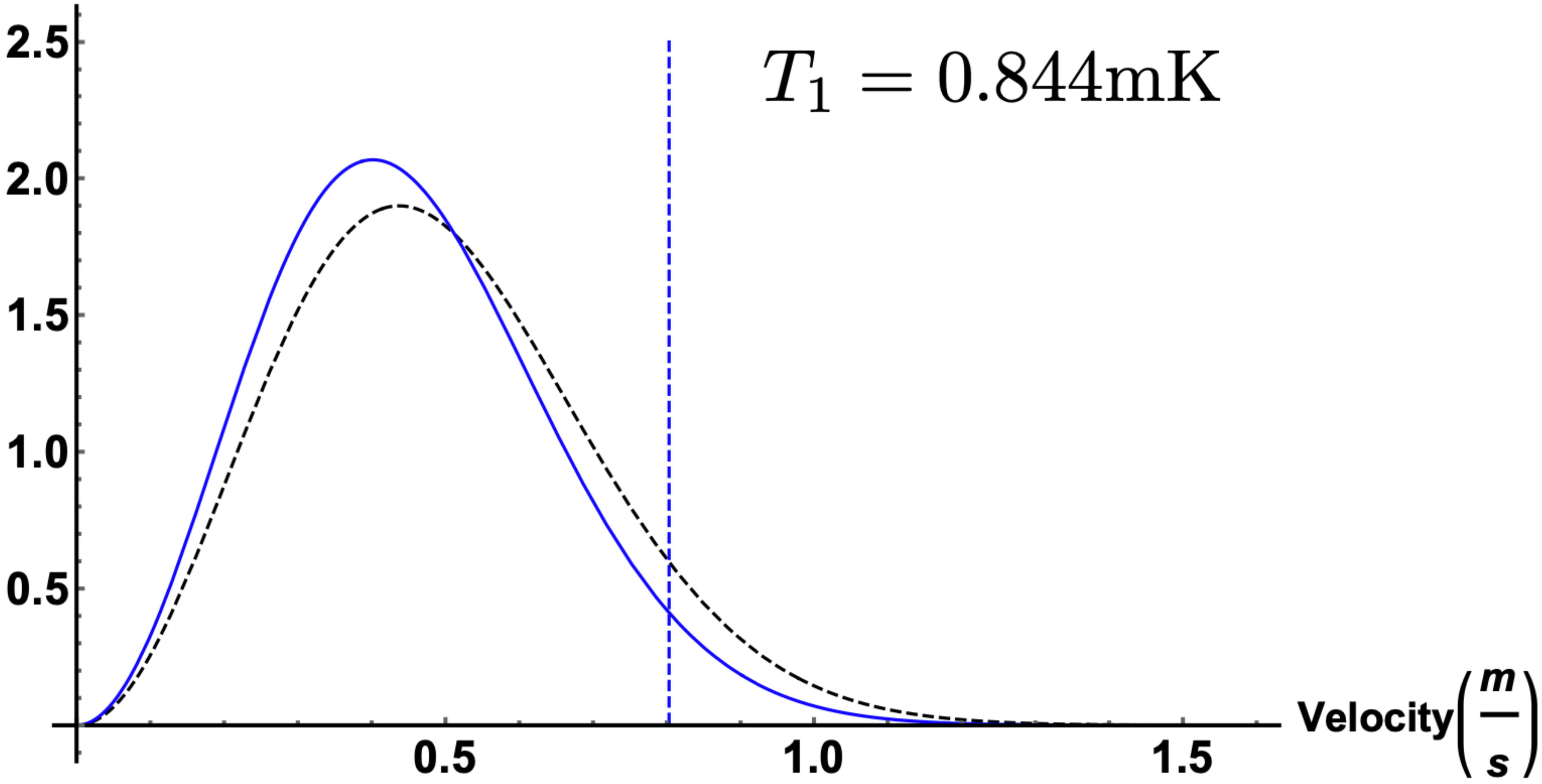
Evaporation cooling



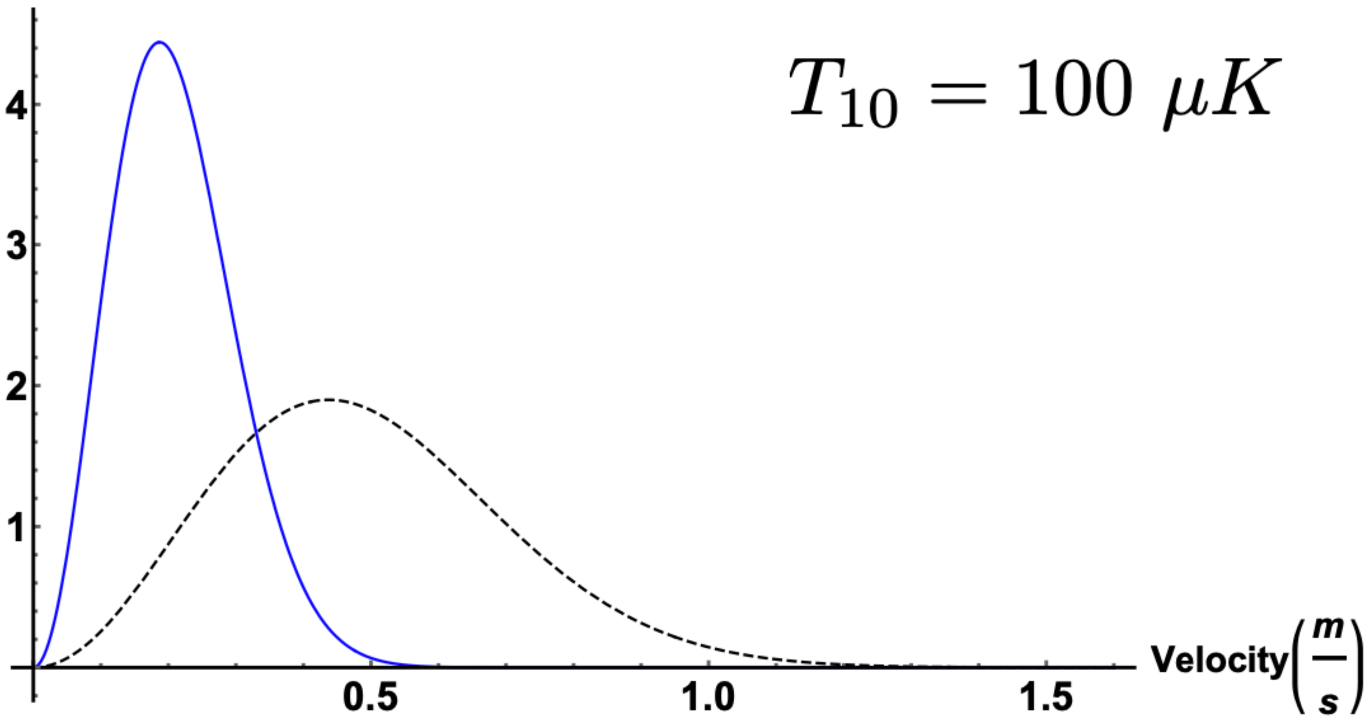
Evaporation cooling in a trapped gas

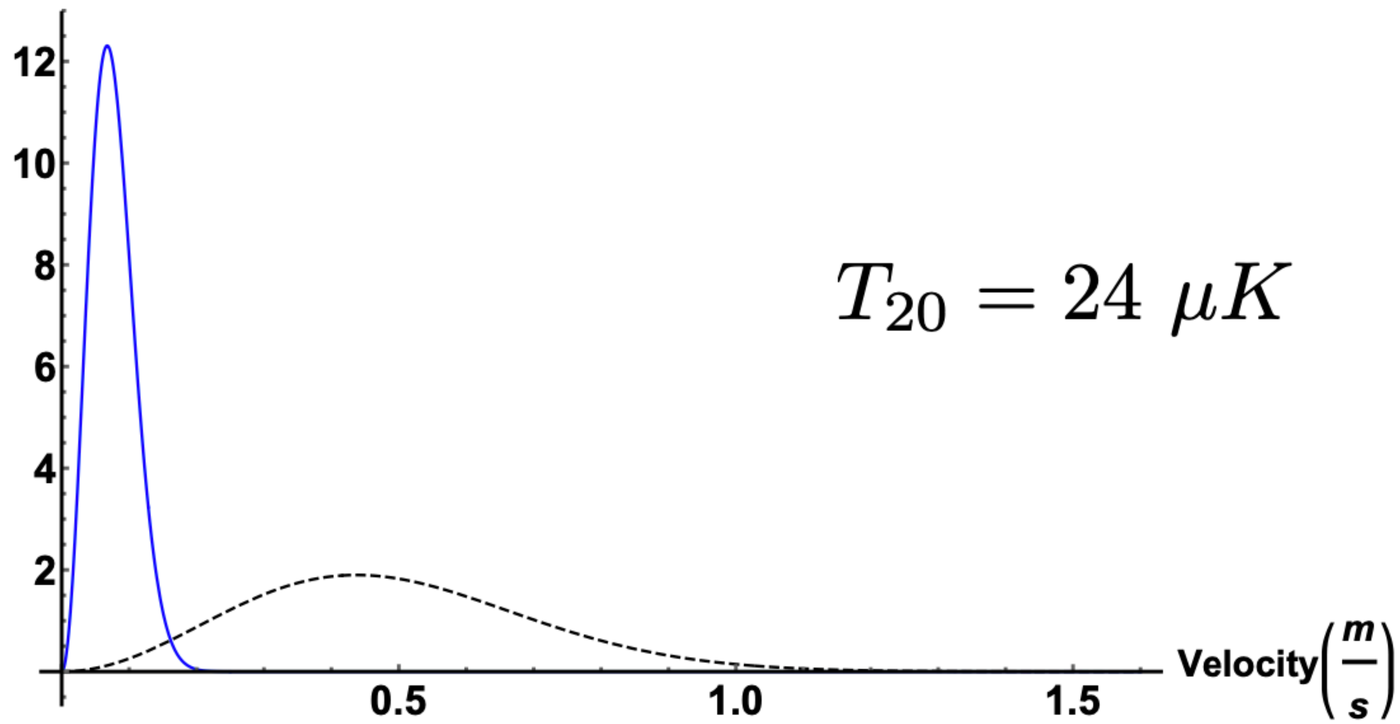


Evaporation cooling in a trapped gas



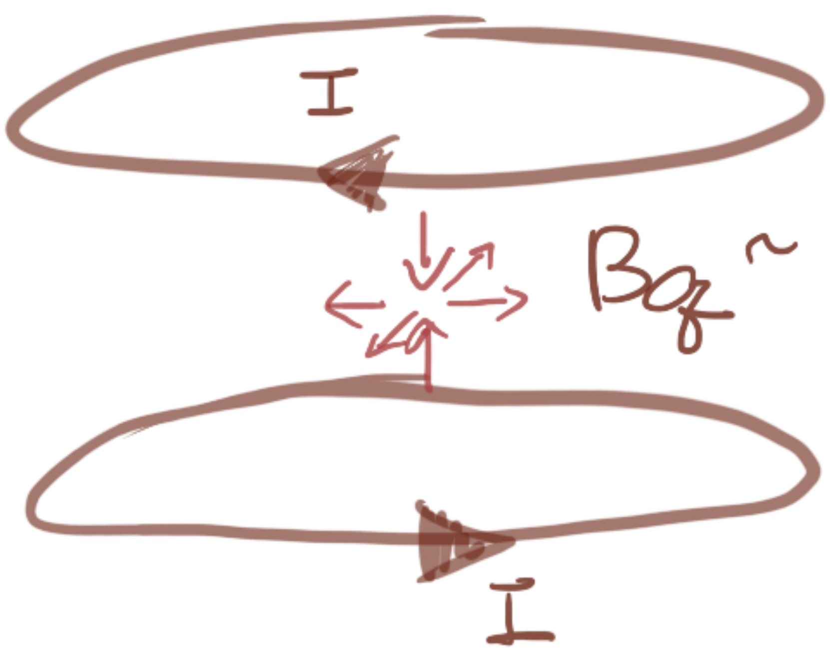
Evaporation cooling in a trapped gas

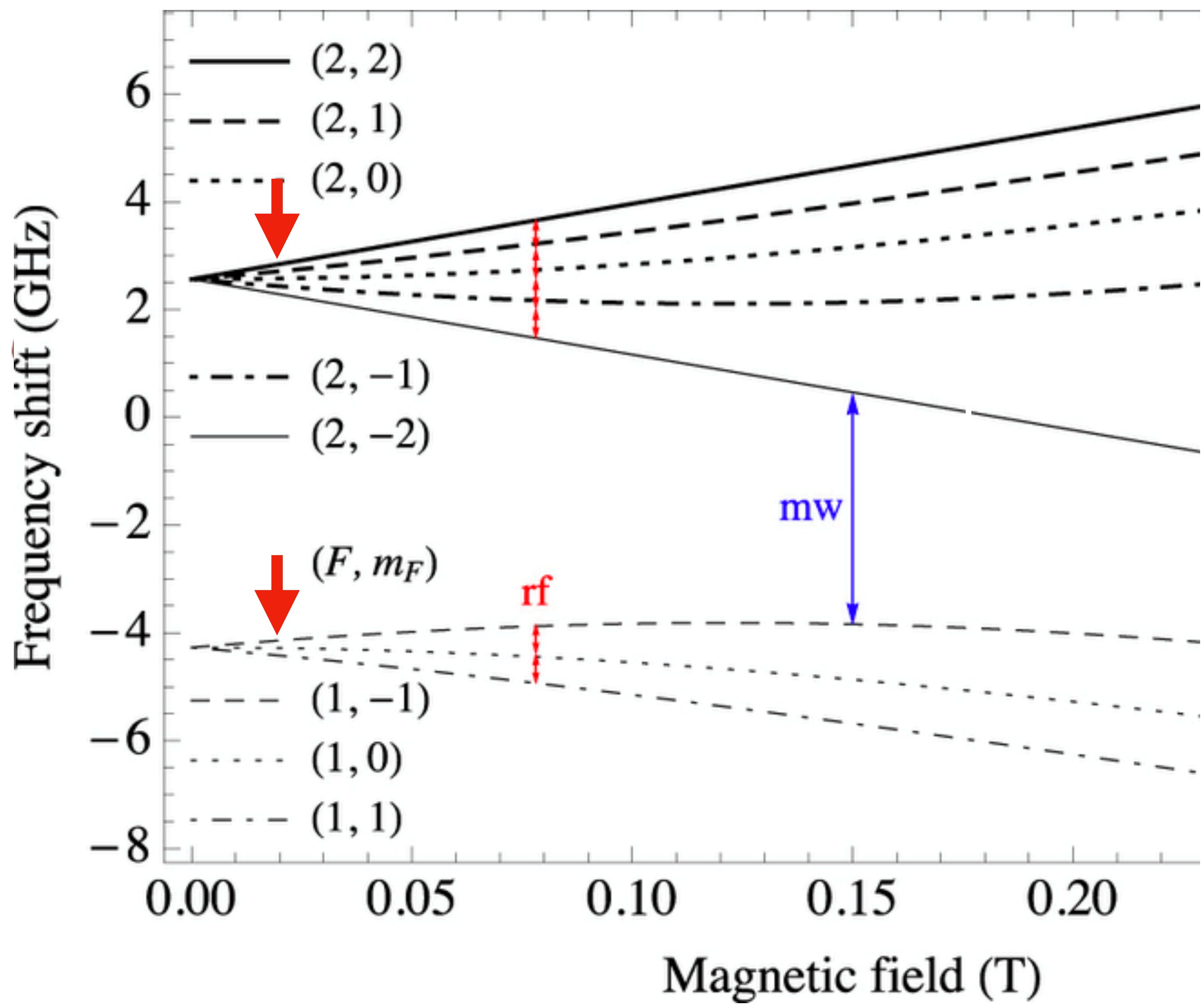




Trapping and cooling atoms in magnetic trap

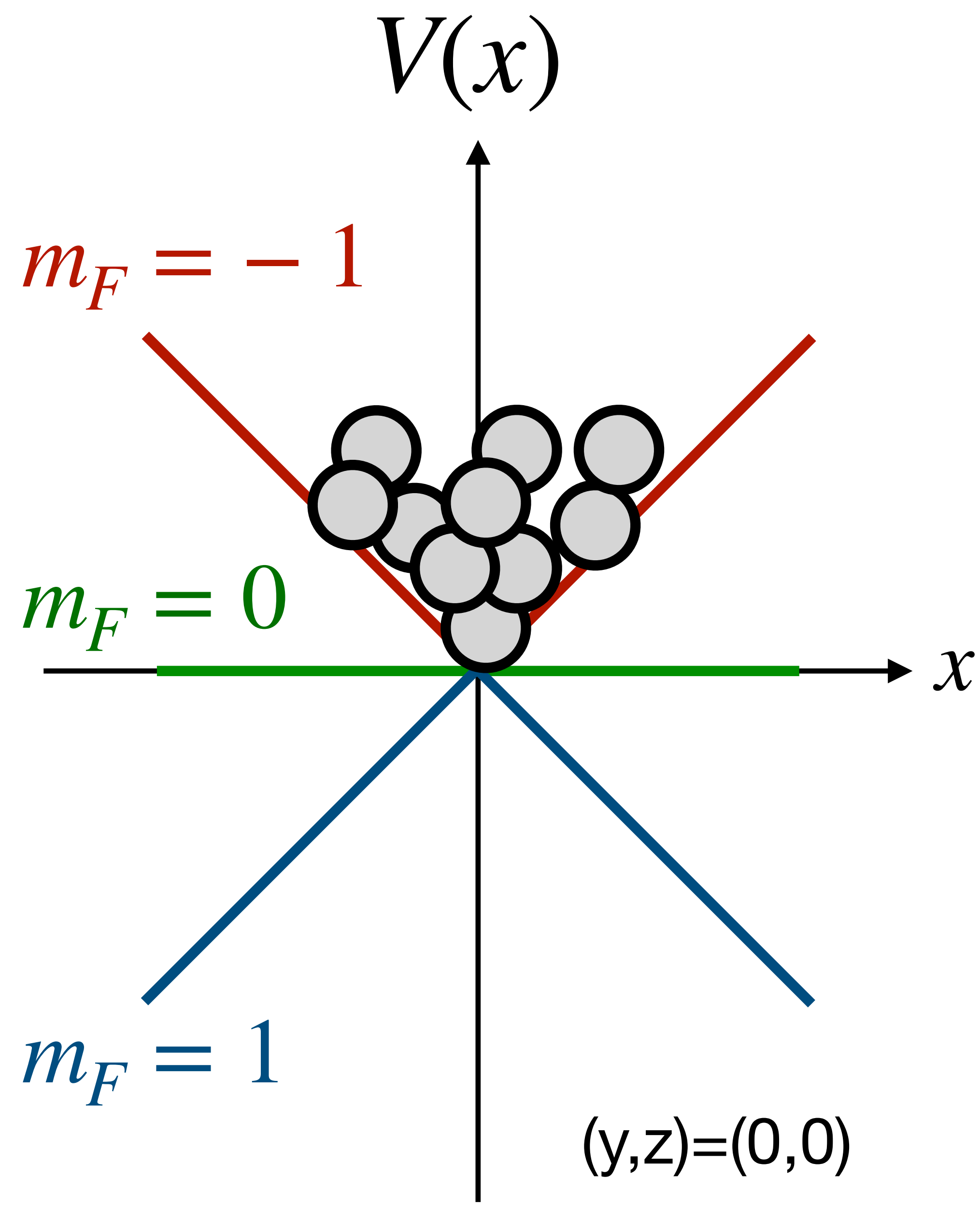
Quadrupole magnetic trap





Low-field seeking state can be trapped at the center !!

Quadrupole trap of neutral atoms



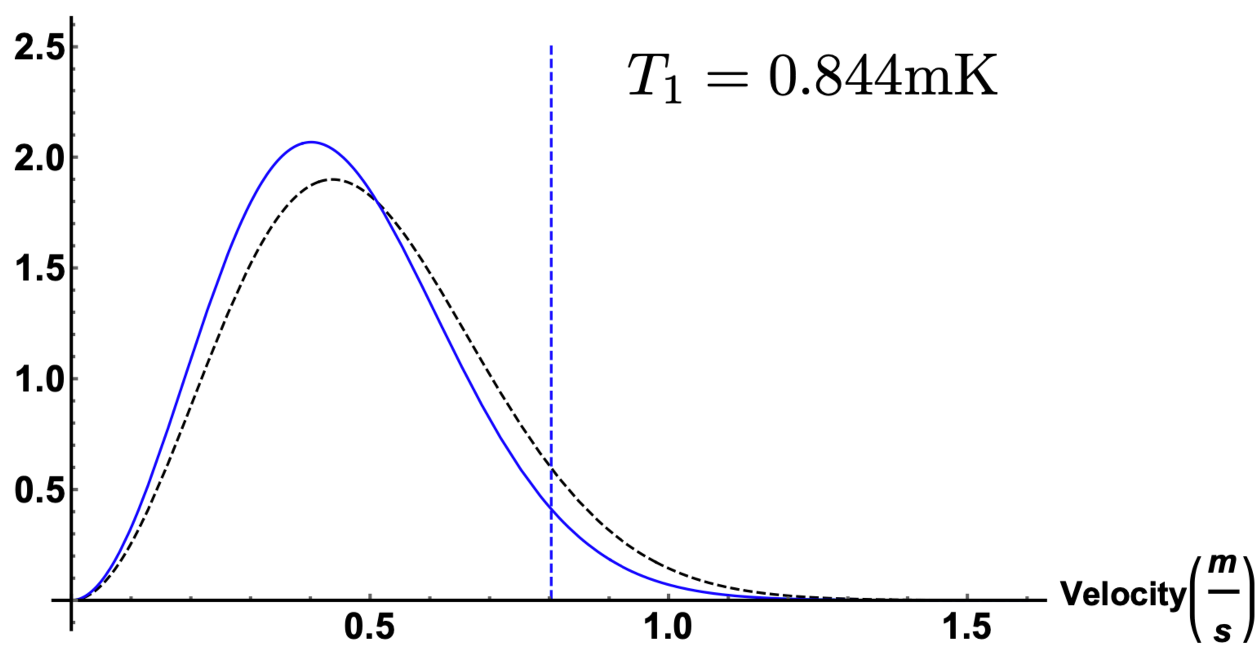
In the low-field regime, the trapping potential to F=1 state

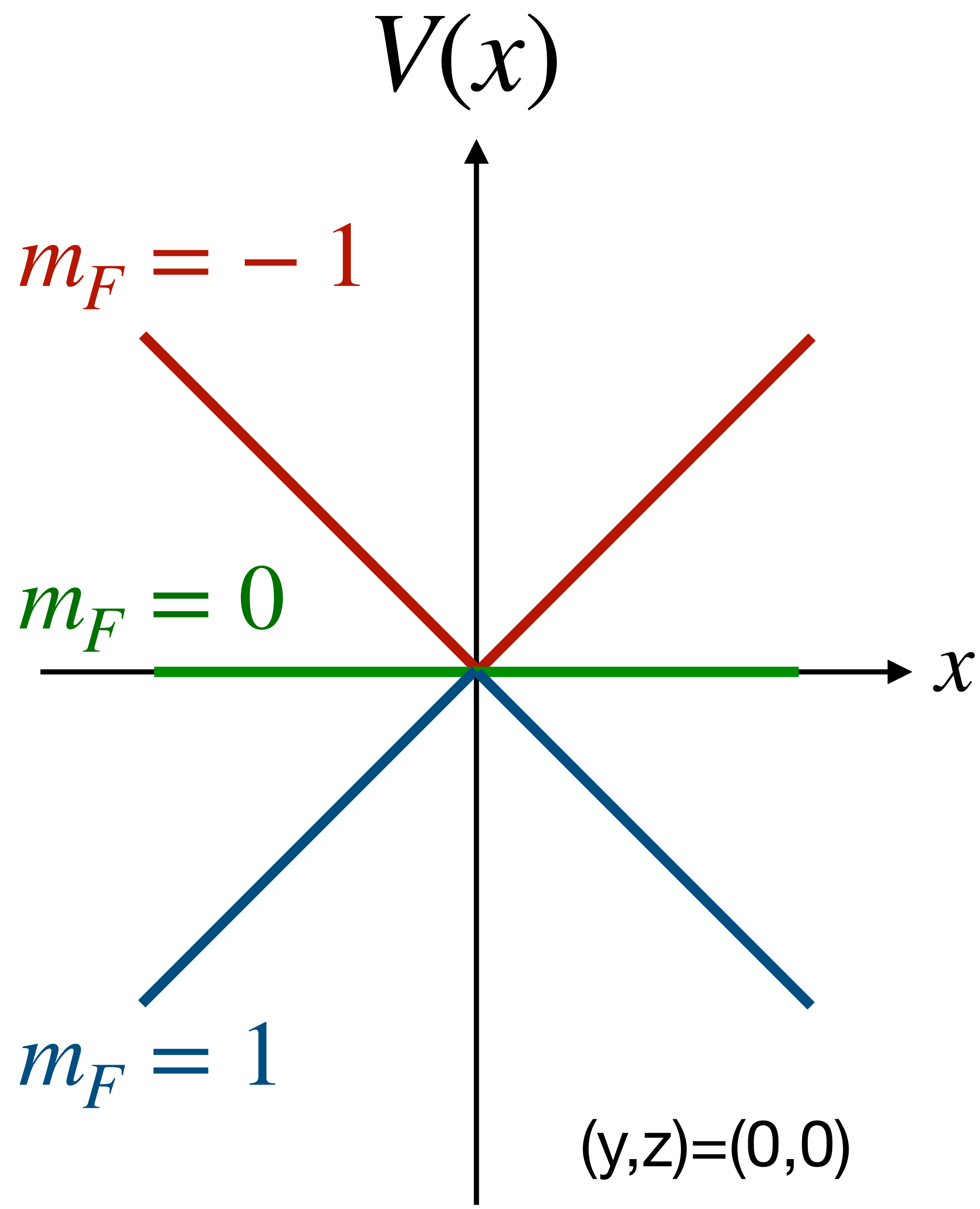
$$V(r) = -\mu \cdot B \propto -m_F B_q \sqrt{x^2 + y^2 + 4z^2}$$

Ramping up the magnetic field, only $|F=1, m_F=-1\rangle$ state are trapped

Evaporation cooling in a quadrupole magnetic trap

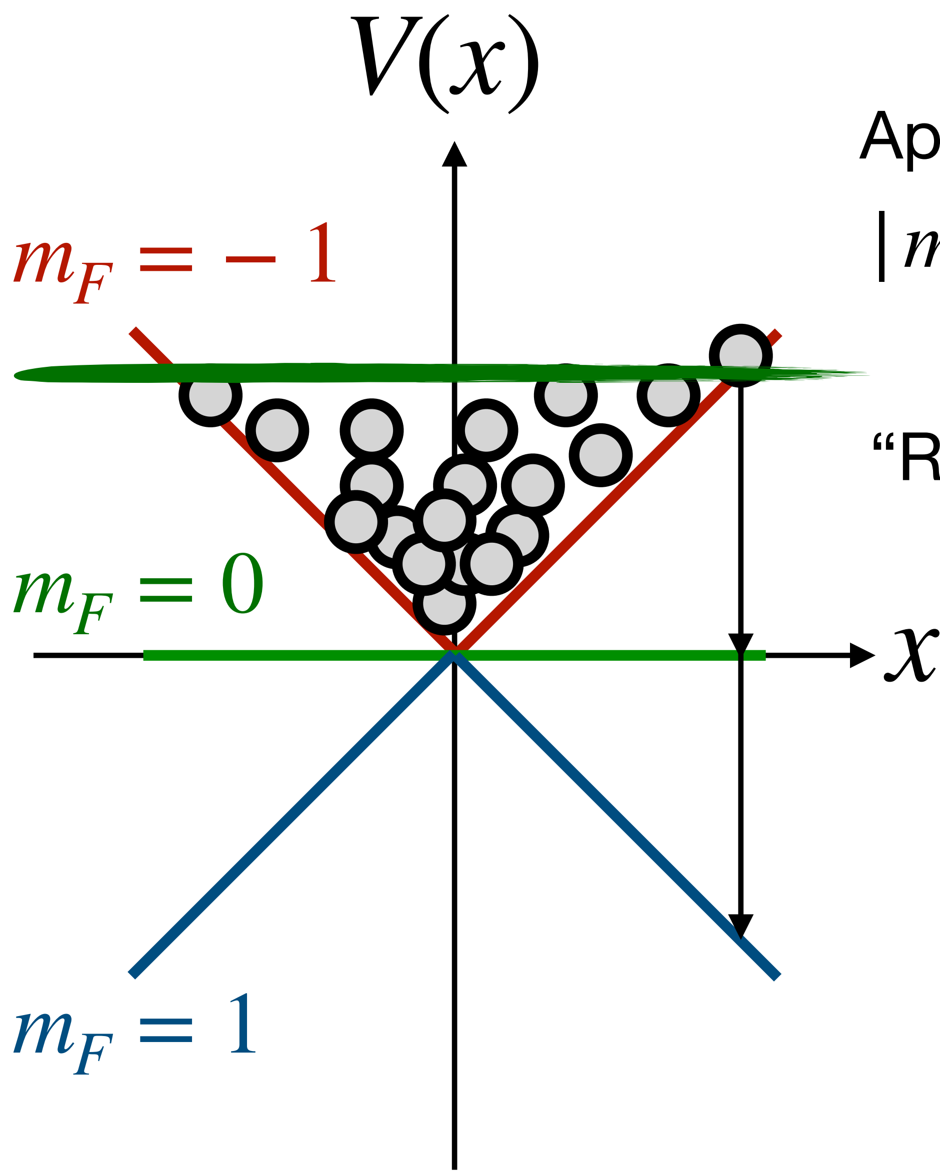
Key idea of the evaporation cooling is to selectively remove atoms with high energy





We can manipulate the spin state of the atoms !!

Evaporation cooling in a quadrupole magnetic trap

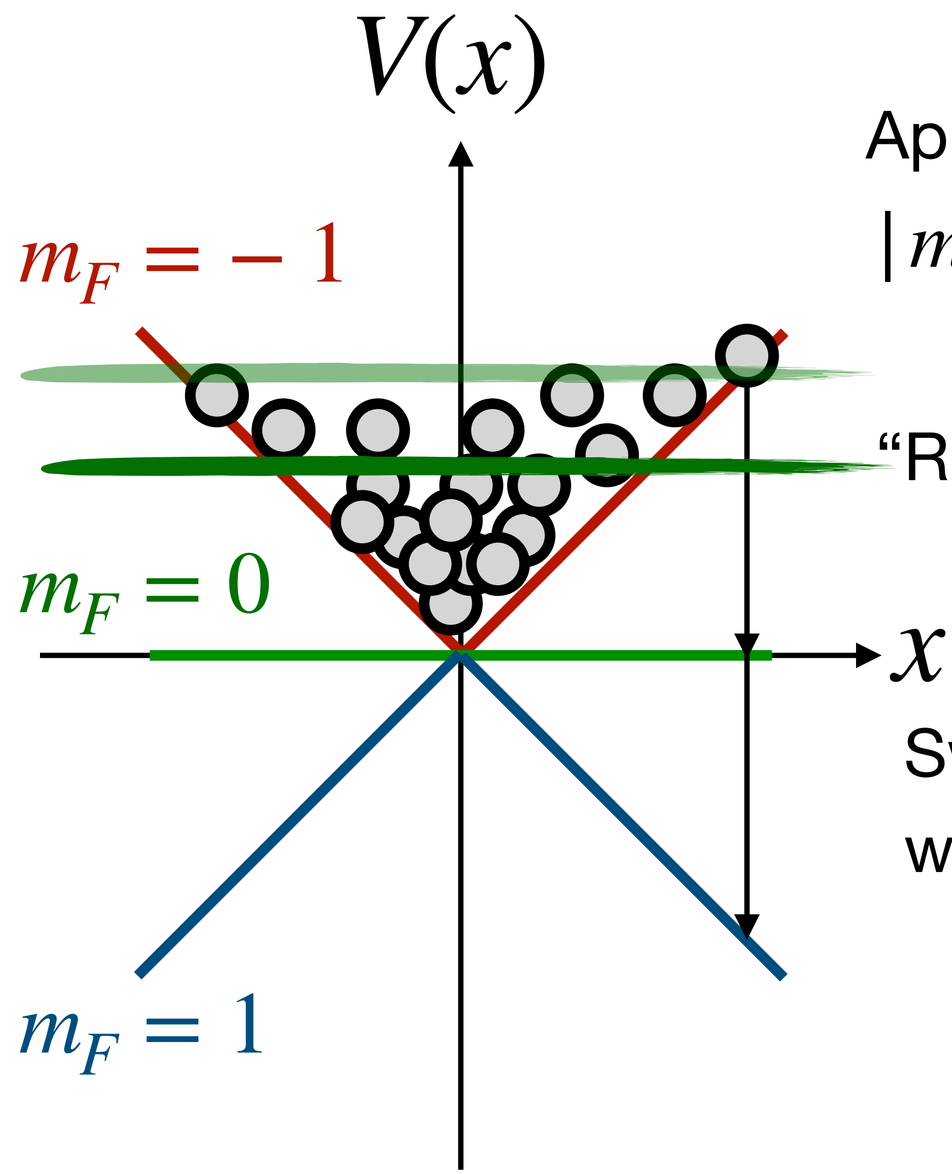


Applying RF to induce spin flip

$|m_F = -1\rangle \rightarrow |m_F = 0\rangle \rightarrow |m_F = -1\rangle$

“RF” knife to remove the high energy atoms !!

Evaporation cooling in a quadrupole magnetic trap



Applying RF to induce spin flip

$|m_F = -1\rangle \rightarrow |m_F = 0\rangle \rightarrow |m_F = -1\rangle$

"RF" knife to remove the high energy atoms !!

Sweep the frequency from high to low,
we can selectively remove high energetic atoms

Bose-Einstein condensation

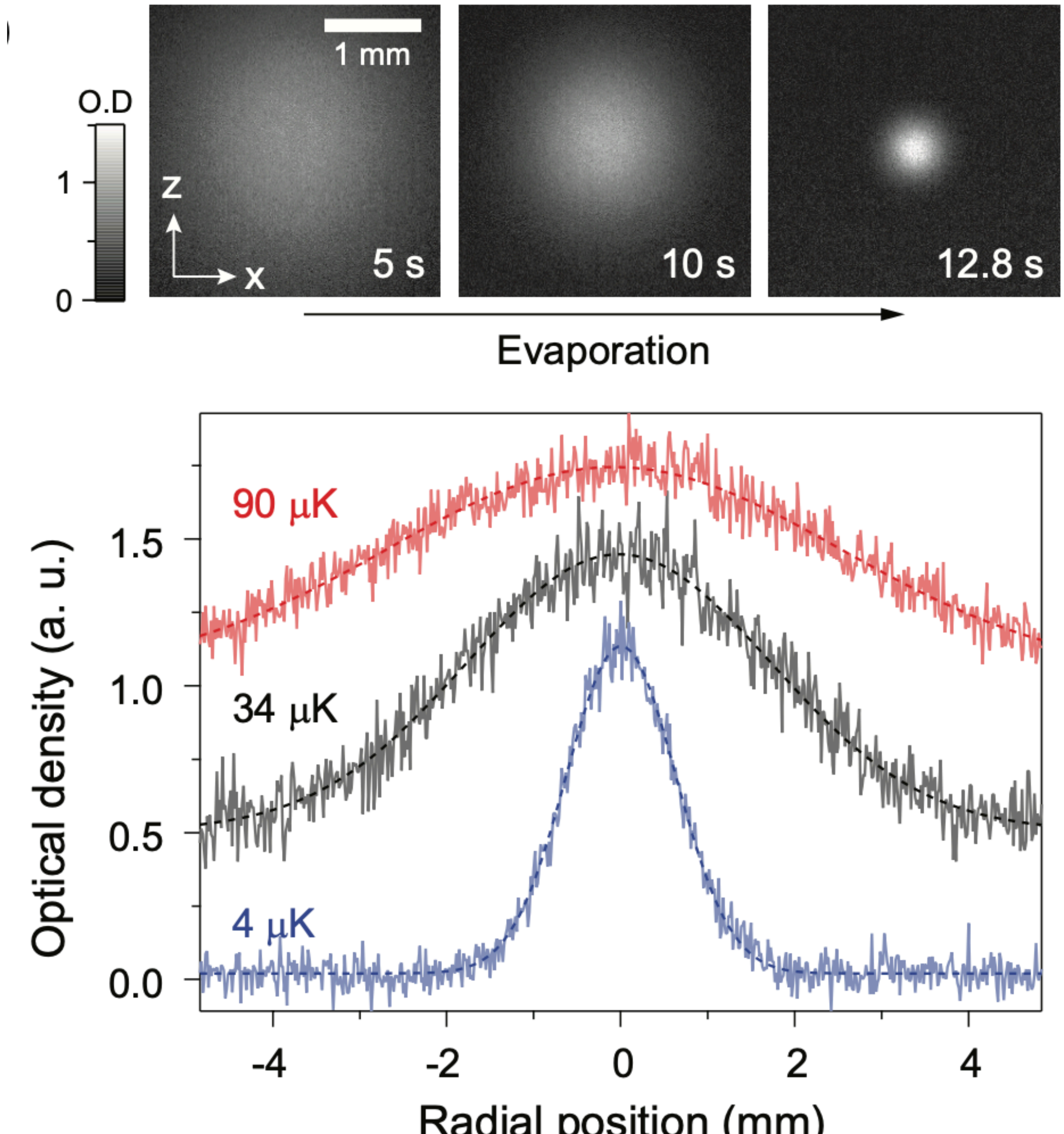
VOLUME 74, NUMBER 26 PHYSICAL REVIEW LETTERS 26 JUNE 1995

Evaporative Cooling of Sodium Atoms

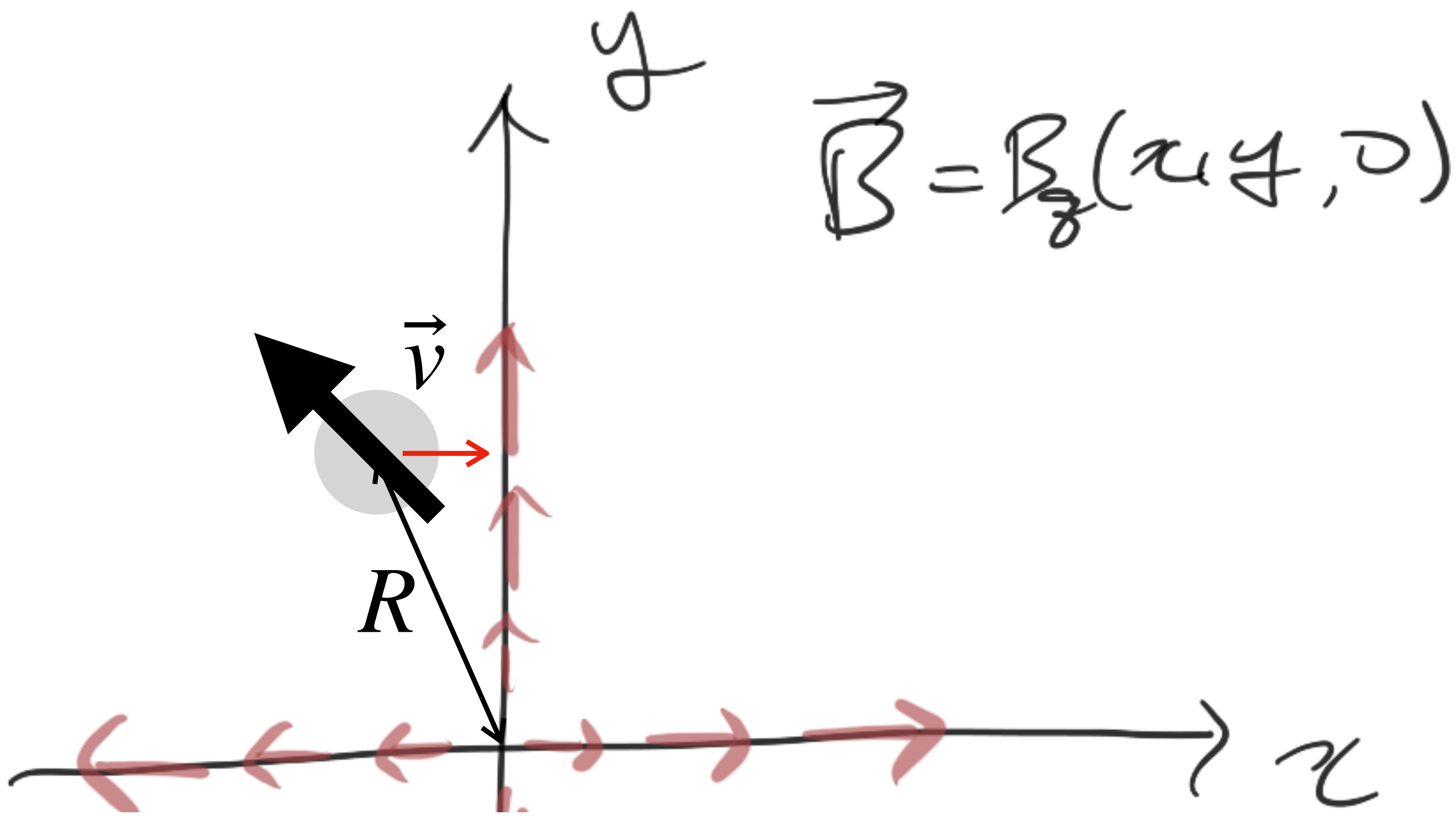
Kendall B. Davis, Marc-Oliver Mewes, Michael A. Joffe, Michael R. Andrews, and Wolfgang Ketterle
Department of Physics and Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139
(Received 28 December 1994)

We have observed evaporative cooling of magnetically trapped sodium atoms. A novel technique, rf induced evaporation, was used to reduce the temperature by a factor of 12 and increase the phase space density by more than 2 orders of magnitude. The elastic collision cross section of cold sodium atoms in the $F = 1$, $m_F = -1$ hyperfine state was determined to be 6×10^{-12} cm^2, which implies a positive value of the scattering length.

Phys.Rev.Lett. **74**. 5202 (1995)


1 mm
O.D
1
0
z
x
5 s
10 s
12.8 s
Evaporation
90 μK
34 μK
4 μK
Optical density (a. u.)
1.5
1.0
0.5
0.0
-4
-2
0
2
4
Radial position (mm)

Non-adiabatic spin flip loss & heating

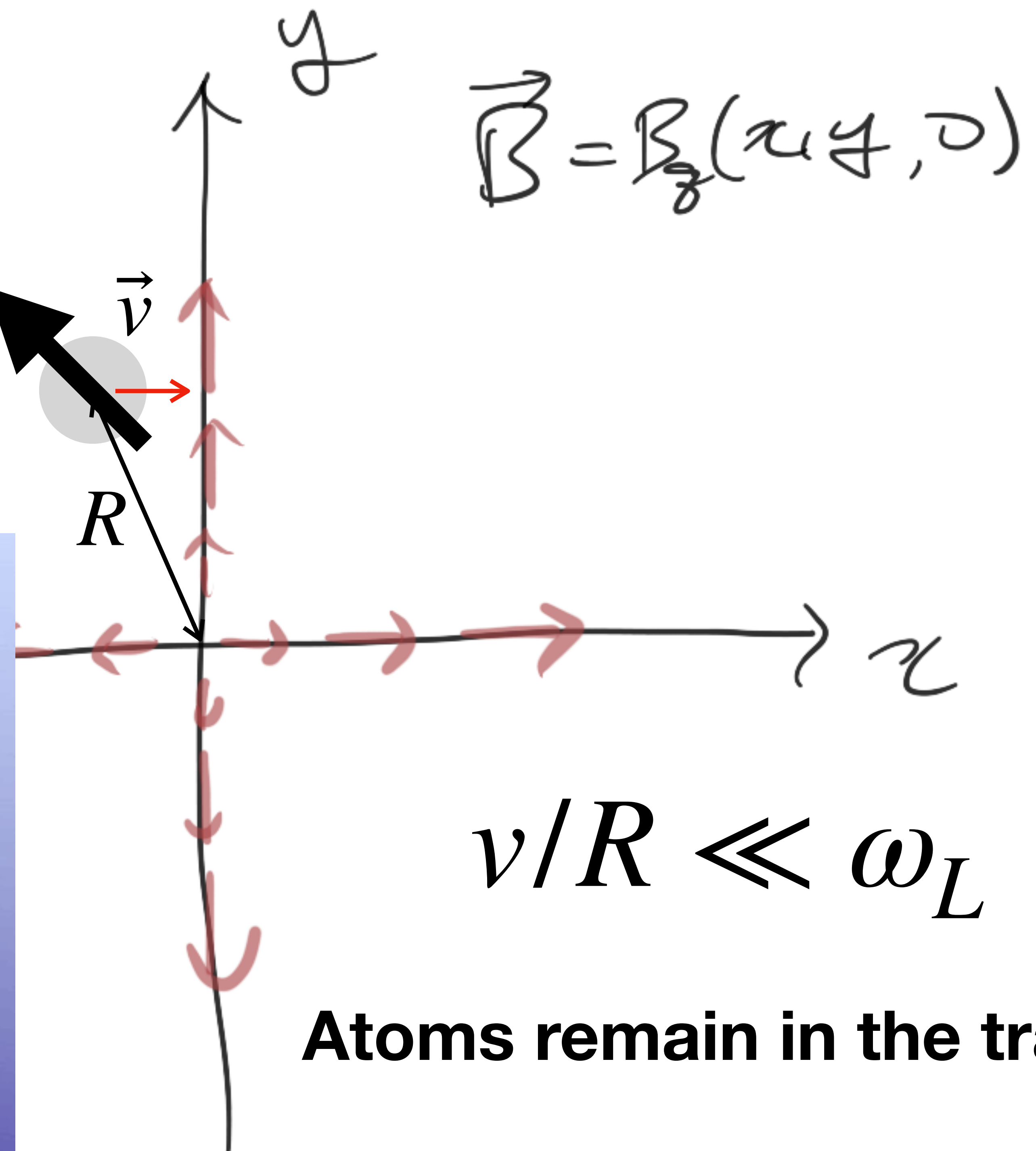


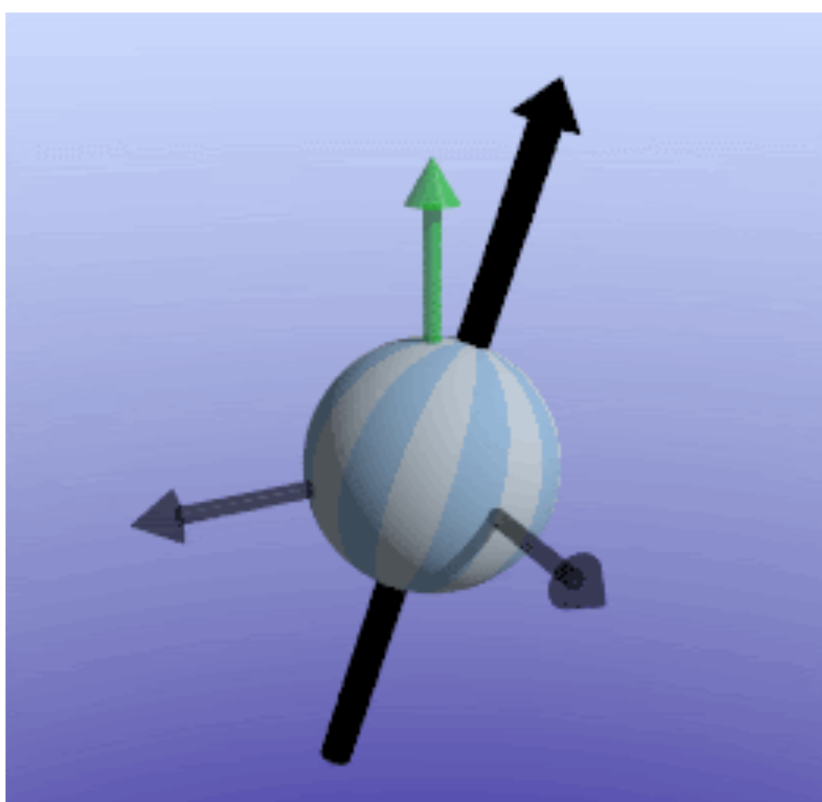
Questions:

For a **moving** atoms, what would be trapping conditions?

A: Atomic spin state should follow the field direction

Non-adiabatic spin flip loss & heating

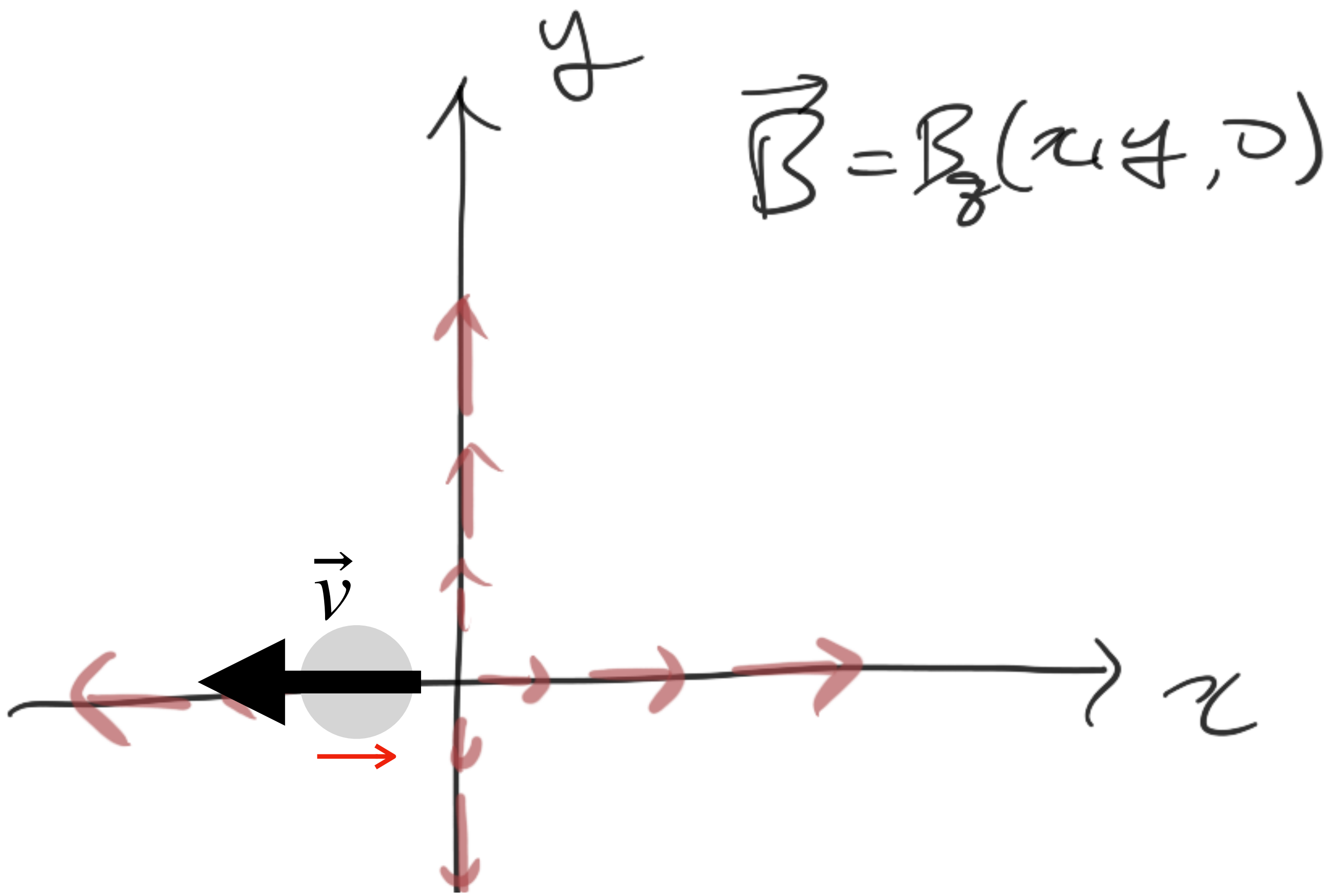




$$v/R \ll \omega_L$$

Atoms remain in the trap!!

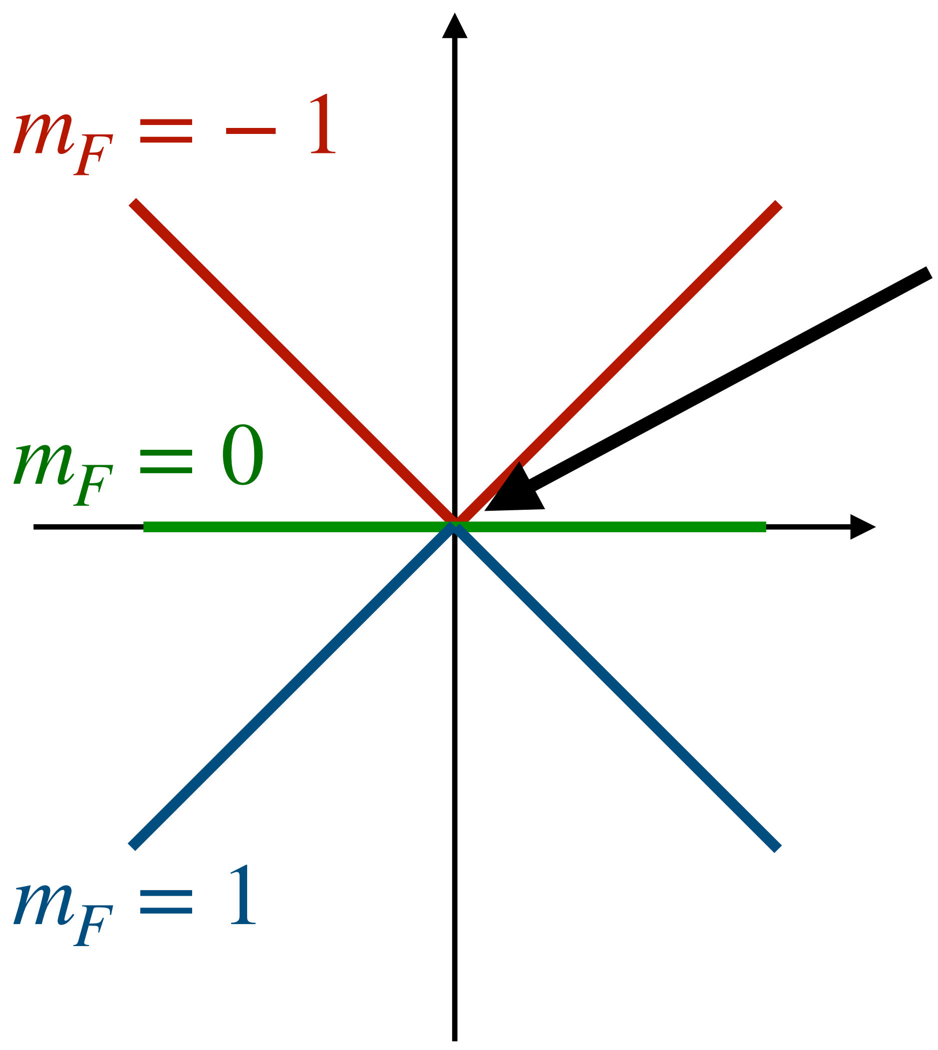
Non-adiabatic spin flip loss & heating



Near the trap center,

the adiabaticity condition breaks down !!!

Non-adiabatic spin flip loss & heating



Atom loss at the trap center

: low energy atoms are lost

: short lifetime & heating occurs

$$\Gamma = \frac{\hbar}{m}\left(\frac{\mu B_q}{k_B T}\right)^2$$

Bose-Einstein condensation

VOLUME 74, NUMBER 26 PHYSICAL REVIEW LETTERS 26 JUNE 1995

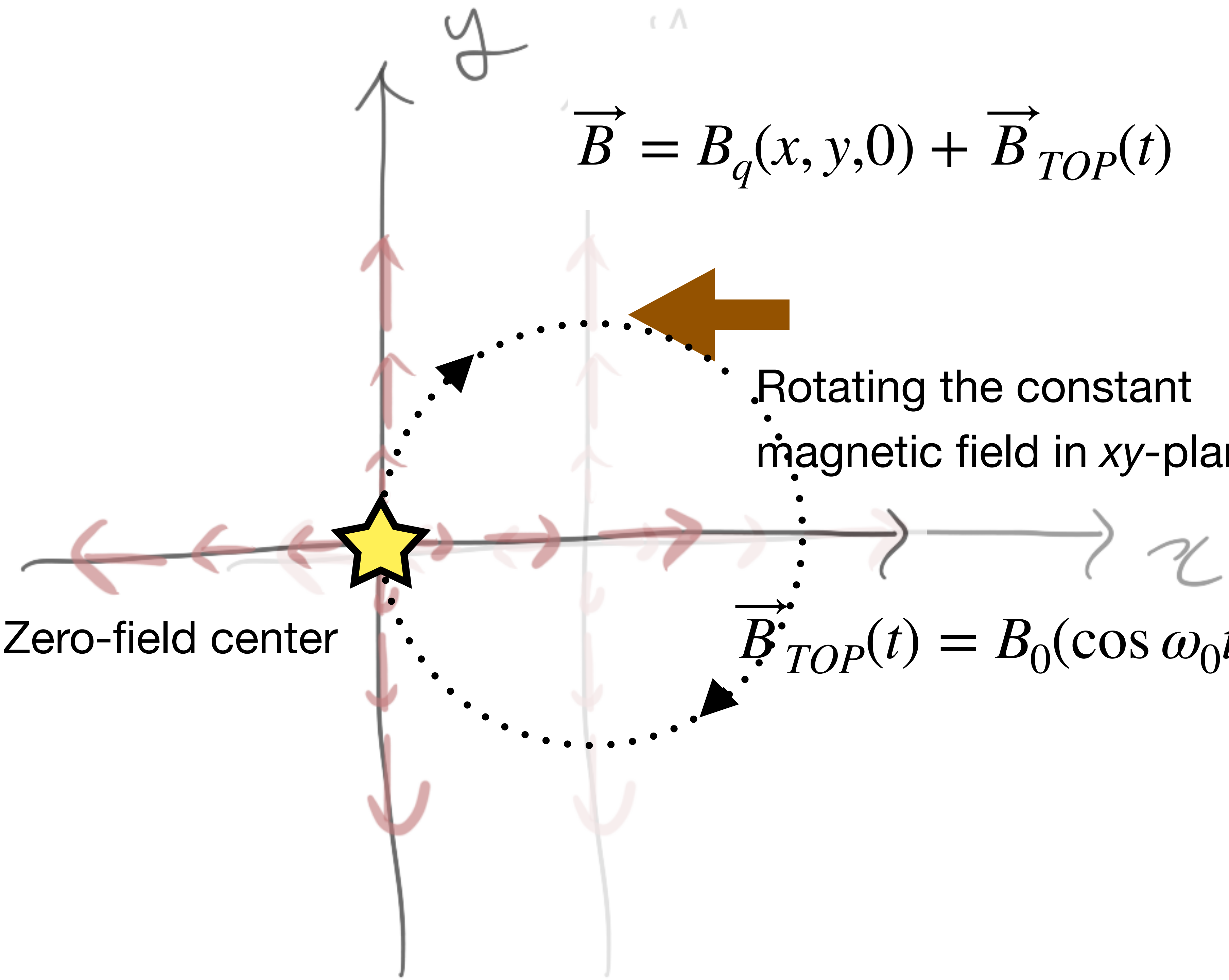
The current limitation of our evaporative cooling is an observed increased trap loss for small atom clouds. For the coldest temperatures achieved, the trapping time decreases from 30 s to a few seconds. This is most probably due to Majorana flops, nonadiabatic transitions to an untrapped state which happen in the center of the trap near the zero of the magnetic field. It may be shown that this loss rate is proportional to the ratio of the area of the "nonadiabatic" region around the center to the cross-sectional area of the cloud. From a Landau-Zener model we estimate the lifetime to be $500d^2$ (in seconds), where d is the cloud diameter in mm. The observed decrease in trapping time for cloud sizes of 100 μm is in qualitative agreement with this model.

Bose-Einstein condensation

How to overcome this difficulty?

- Design a new trap without such zero-field (D. Pritchard, R. Hulet)
- Try a new idea (E. Cornell, C. Wieman, W. Ketterle)

Time-orbiting trap

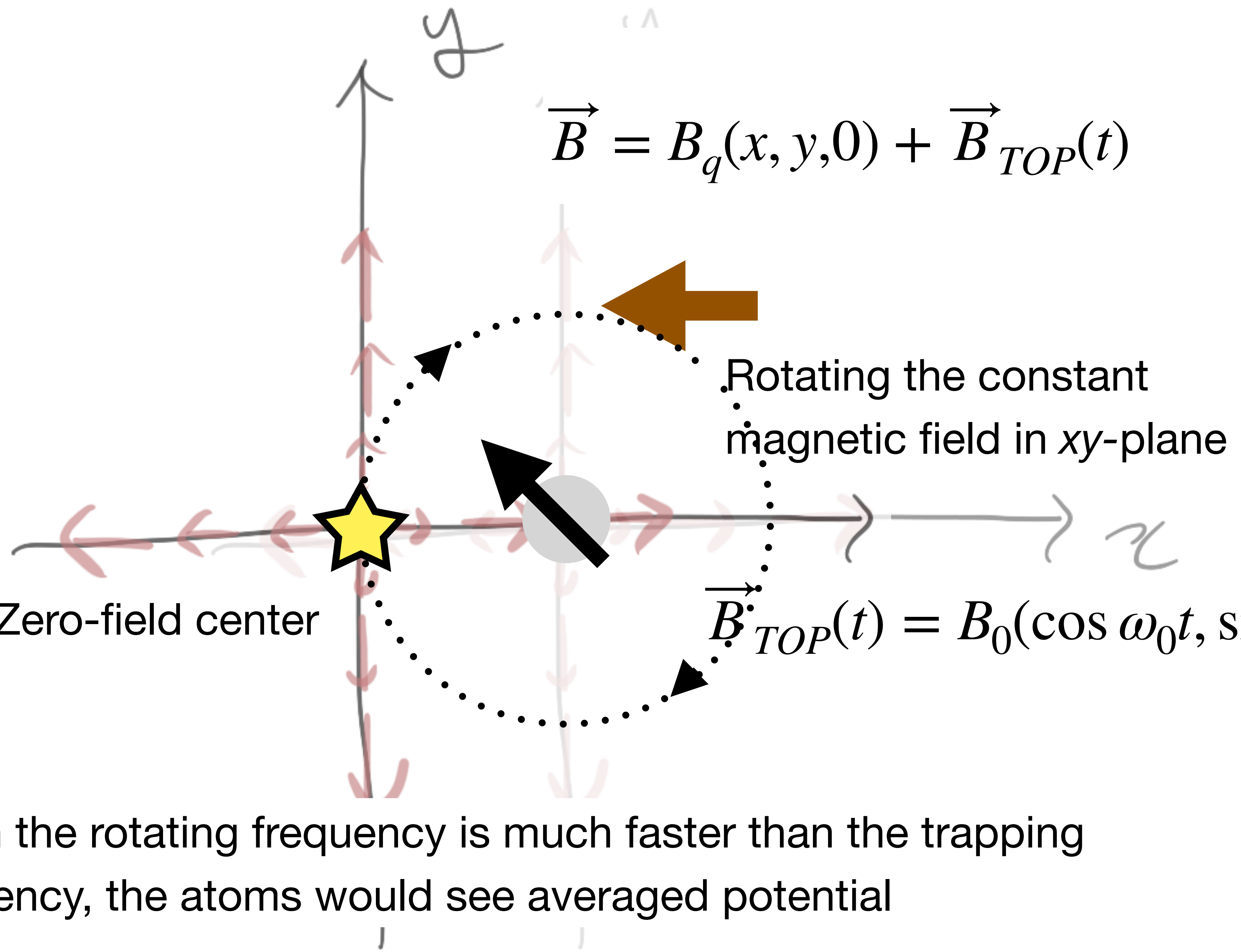


$$\vec{B} = B_q(x, y, 0) + \vec{B}_{TOP}(t)$$

$$\vec{B}_{TOP}(t) = B_0(\cos\omega_0 t, \sin\omega_0 t, 0)$$

Time-orbiting trap

$$\overrightarrow{B} = B_q(x, y, 0) + \overrightarrow{B}_{TOP}(t)$$



$$\overrightarrow{B}_{TOP}(t) = B_0(\cos\omega_0 t, \sin\omega_0 t, 0)$$

When the rotating frequency is much faster than the trapping frequency, the atoms would see averaged potential

Bose-Einstein condensation

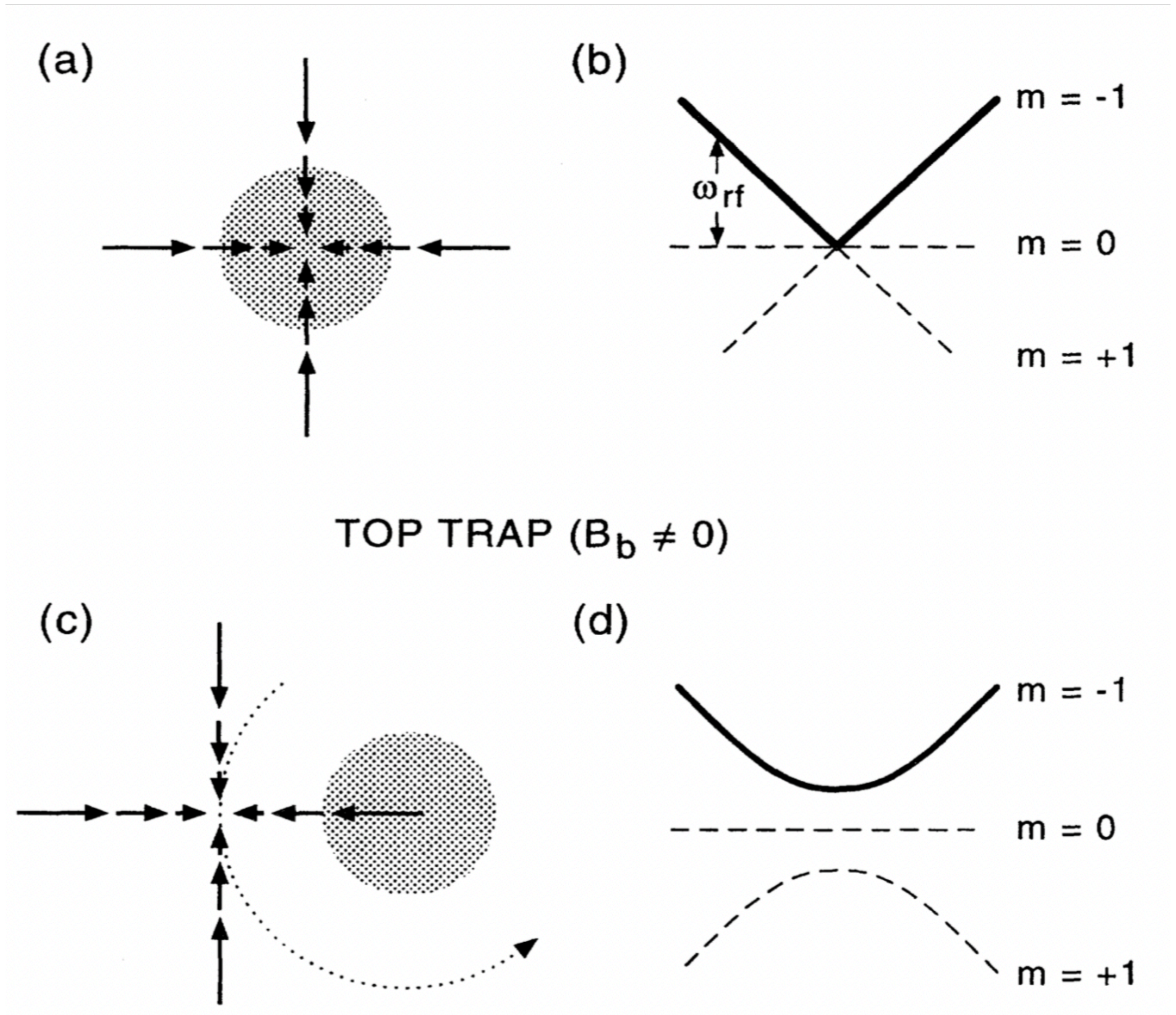
VOLUME 74, NUMBER 17 PHYSICAL REVIEW LETTERS 24 APRIL 1995

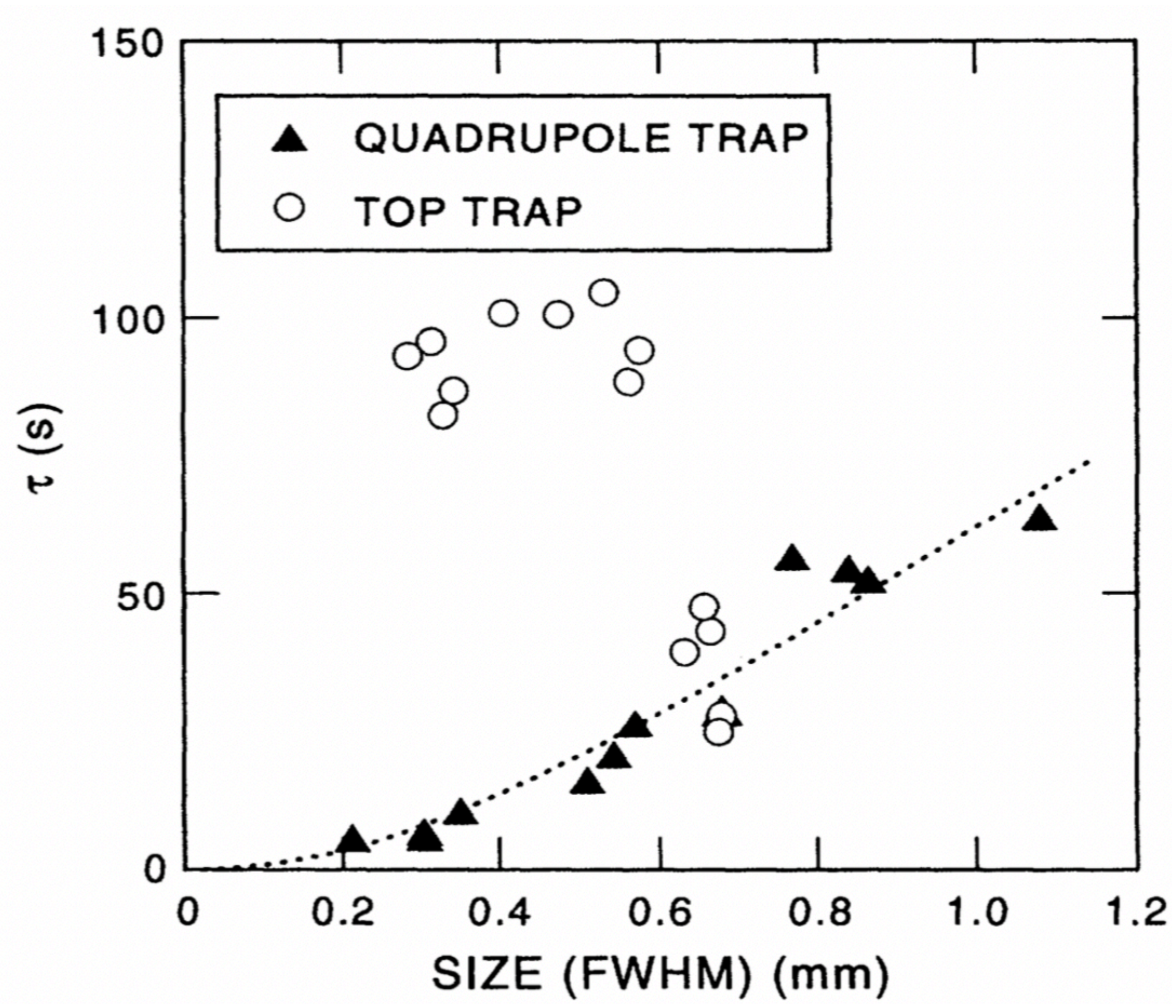
Stable, Tightly Confining Magnetic Trap for Evaporative Cooling of Neutral Atoms

Wolfgang Petrich,* Michael H. Anderson, Jason R. Ensher, and Eric A. Cornell†

Joint Institute for Laboratory Astrophysics, National Institute of Standards and Technology and University of Colorado, and Physics Department, University of Colorado, Boulder, Colorado 80309-0440

(Received 14 November 1994; revised manuscript received 27 February 1995)





Bose-Einstein condensation

VOLUME 74, NUMBER 17 PHYSICAL REVIEW LETTERS 24 APRIL 1995

Stable, Tightly Confining Magnetic Trap for Evaporative Cooling of Neutral Atoms

Wolfgang Petrich,* Michael H. Anderson, Jason R. Ensher, and Eric A. Cornell†
Joint Institute for Laboratory Astrophysics, National Institute of Standards and Technology and University of Colorado, and Physics Department, University of Colorado, Boulder, Colorado 80309-0440
(Received 14 November 1994; revised manuscript received 27 February 1995)

After further evaporation cooling

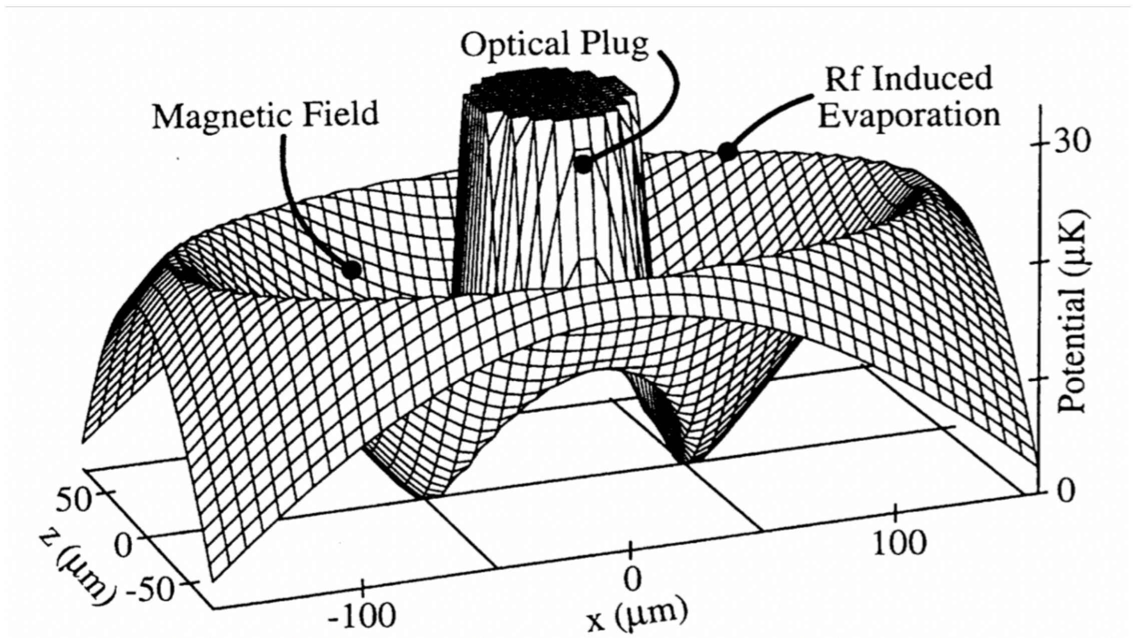
Observation of Bose-Einstein Condensation in a Dilute Atomic Vapor

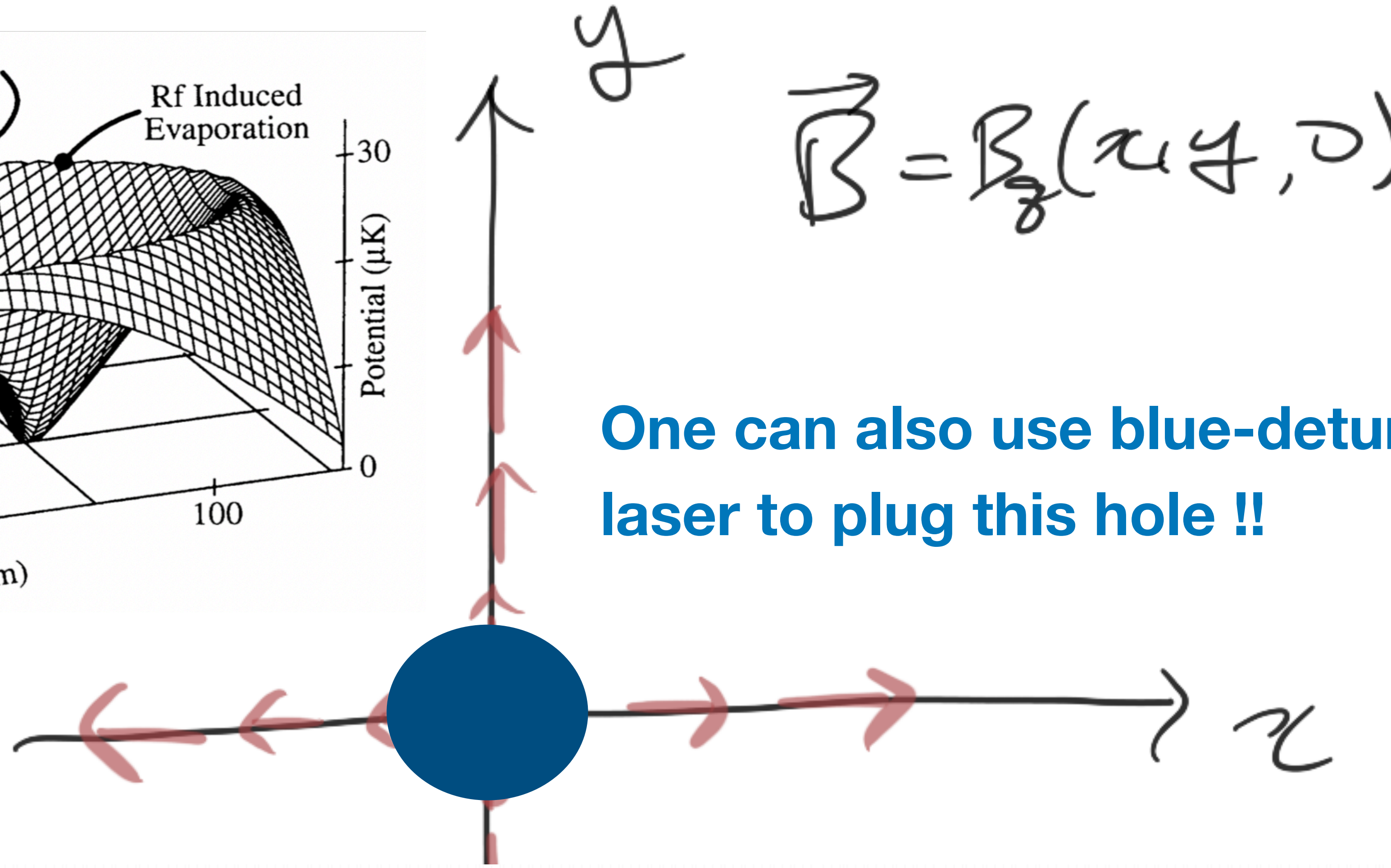
M. H. Anderson, J. R. Ensher, M. R. Matthews, C. E. Wieman,*
E. A. Cornell

A Bose-Einstein condensate was produced in a vapor of rubidium-87 atoms that was confined by magnetic fields and evaporatively cooled. The condensate fraction first appeared near a temperature of 170 nanokelvin and a number density of 2.5×10^{12} per cubic centimeter and could be preserved for more than 15 seconds. Three primary signatures of Bose-Einstein condensation were seen. (i) On top of a broad thermal velocity distribution, a narrow peak appeared that was centered at zero velocity. (ii) The fraction of the atoms that were in this low-velocity peak increased abruptly as the sample temperature was lowered. (iii) The peak exhibited a nonthermal, anisotropic velocity distribution expected of the minimum-energy quantum state of the magnetic trap in contrast to the isotropic, thermal velocity distribution observed in the broad uncondensed fraction.

SCIENCE • VOL. 269 • 14 JULY 1995

Non-adiabatic spin flip loss & heating





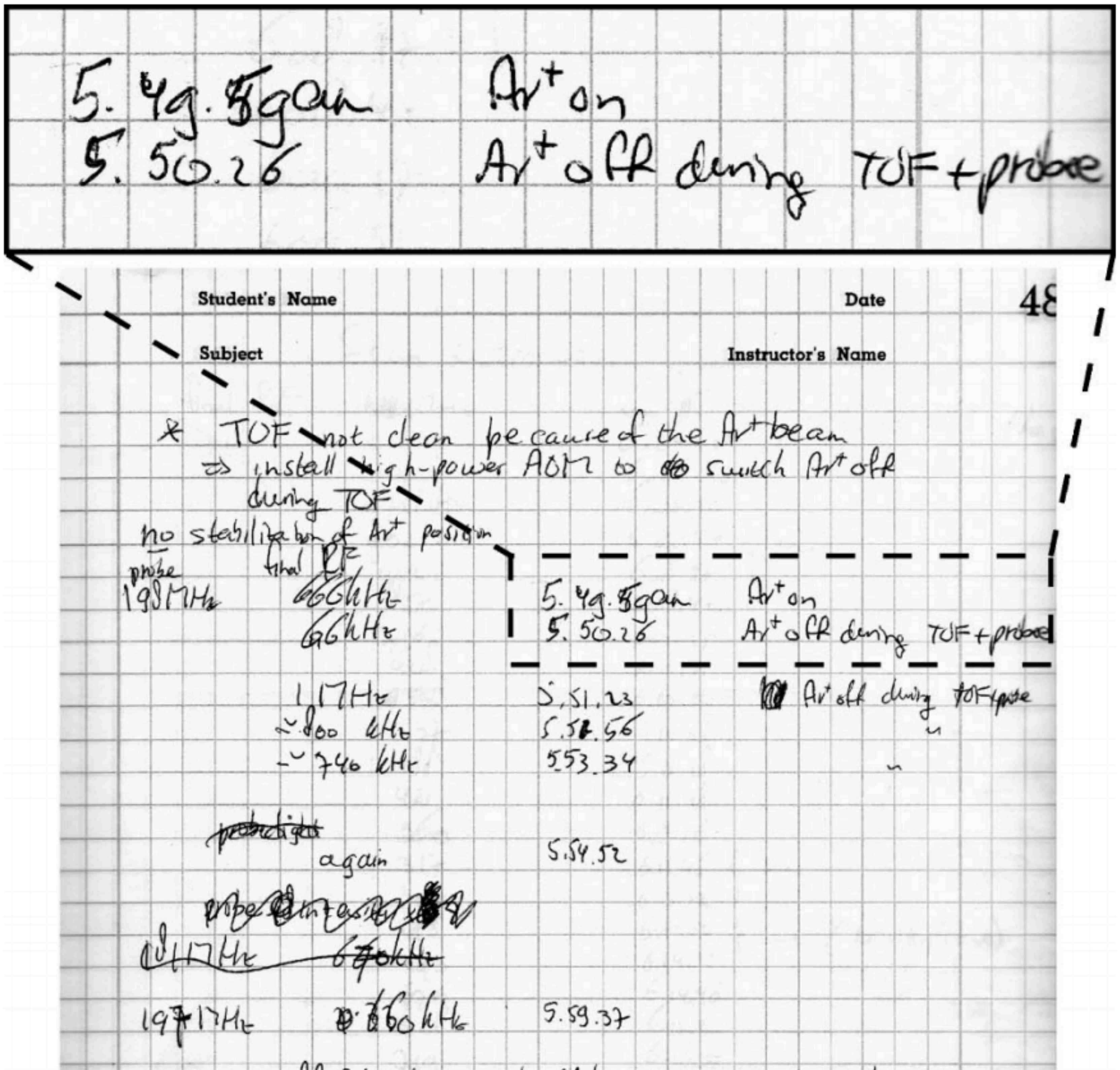
One can also use blue-detuned laser to plug this hole !!

VOLUME 75 | 27 NOVEMBER 1995 | NUMBER 22

Bose-Einstein Condensation in a Gas of Sodium Atoms

K. B. Davis, M.-O. Mewes, M. R. Andrews, N. J. van Druten, D. S. Durfee, D. M. Kurn, and W. Ketterle
Department of Physics and Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139
(Received 17 October 1995)

Bose-Einstein condensation

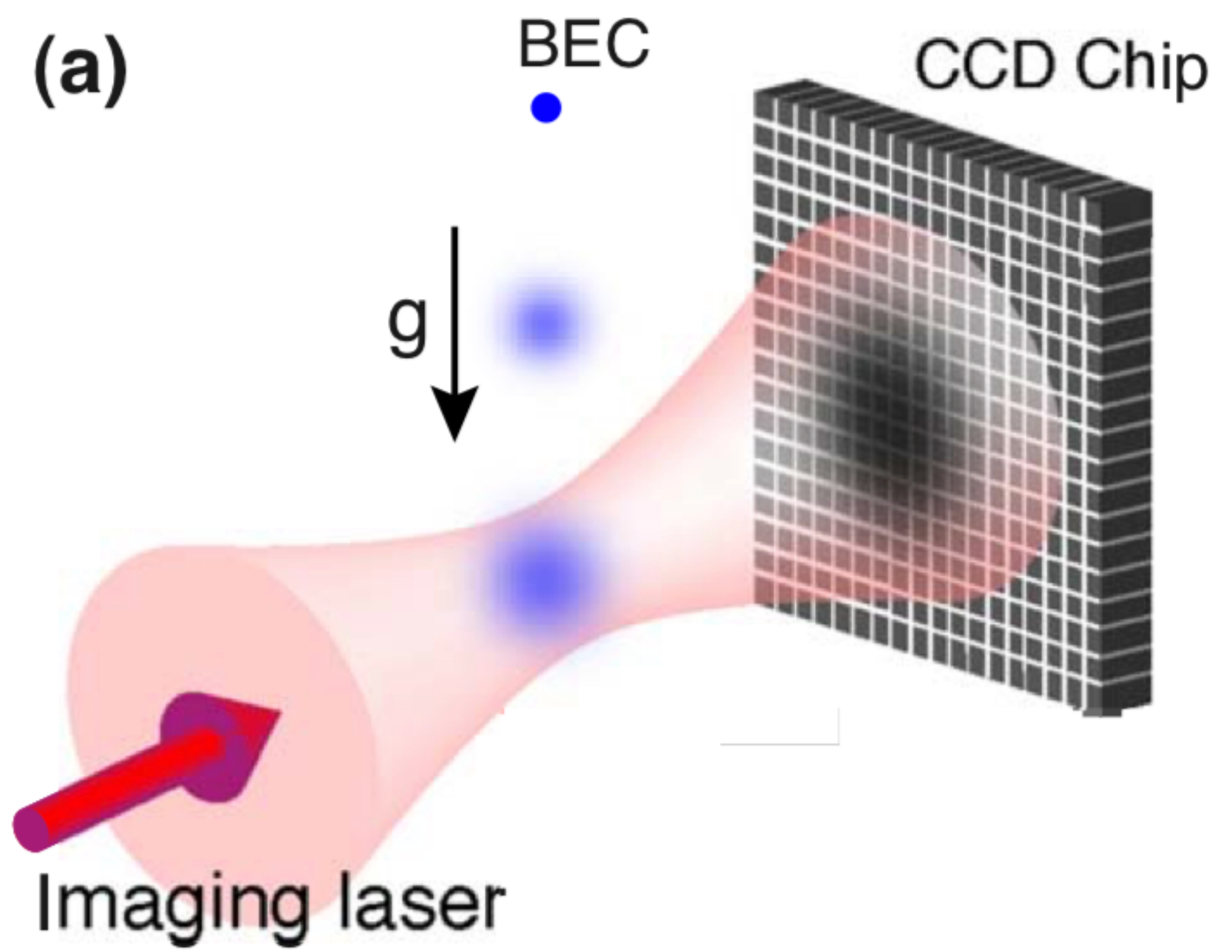

Student's Name Date 48
Subject Instructor's Name

* TOF not clean because of the Ar+ beam
⇒ install high-power AOM to switch Ar+ off during TOF
no stabilization of Ar+ position

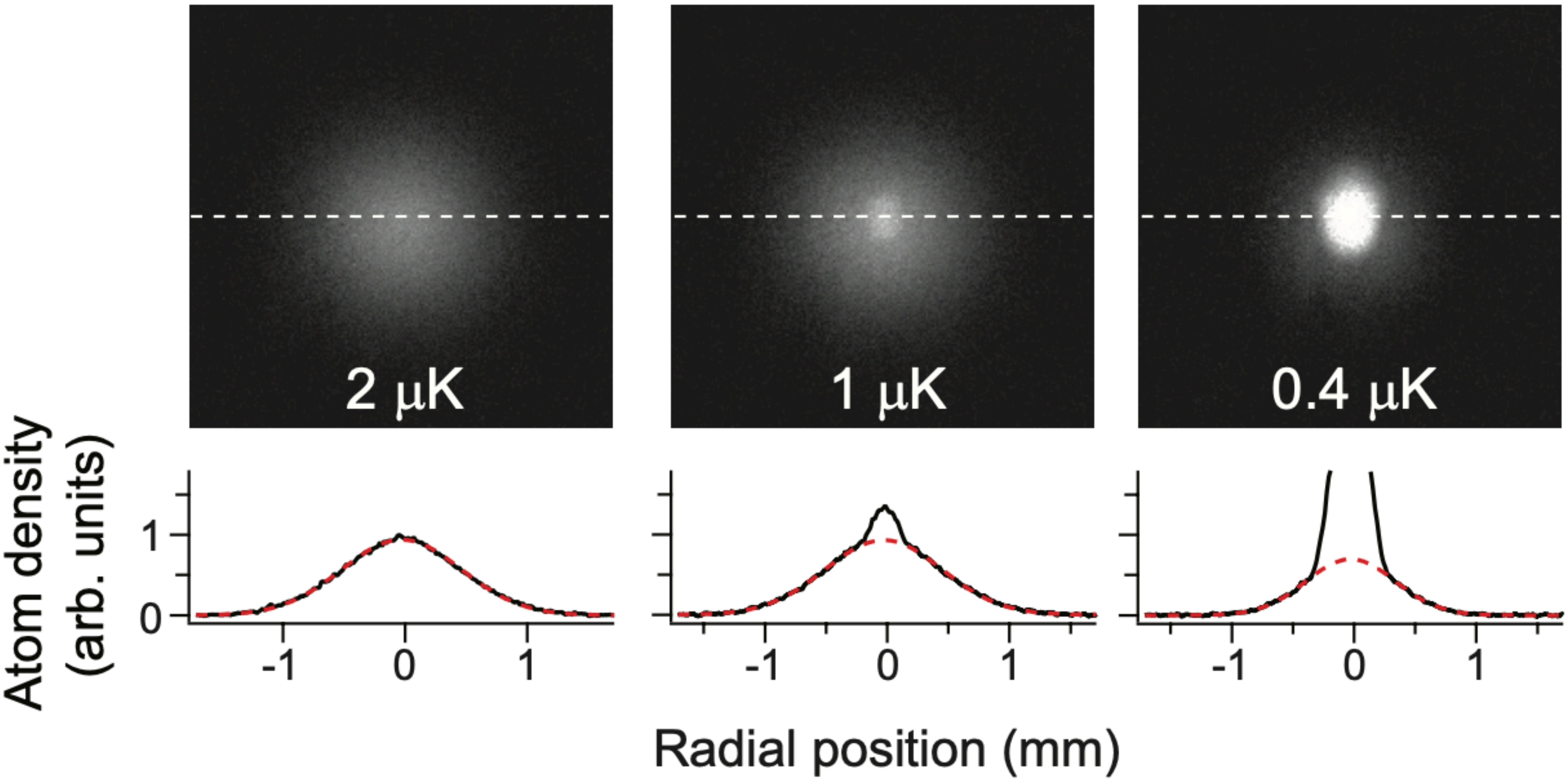
probe	final RF		
198 MHz	66 kHz	5.49.58 am	Ar+ on
	66 kHz	5.50.26	Ar+ off during TOF+probe
	1 MHz	5.51.23	Ar+ off during TOF+probe
	~800 kHz	5.52.56	"
	~740 kHz	5.53.34	"
	again	5.54.52	
197.17 MHz	760 kHz	5.59.37	

How to probe the BEC?

: With sufficient time-of-flight, the image reveals its momentum distributions



Bose-Einstein condensation



Significance of achieving BEC

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  Astrophysical Phenomena; Instrumentation
- Condensed Matter (**cond-mat** new, recent,
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- High Energy Physics – Experiment (**hep-ex**
- High Energy Physics – Lattice (**hep-lat** new
- High Energy Physics – Phenomenology (**he**
- High Energy Physics – Theory (**hep-th** new
- Mathematical Physics (**math-ph** new, recer
- Nonlinear Sciences (**nlin** new, recent, searc
  includes: Adaptation and Self-Organizing S
  Formation and Solitons
- Nuclear Experiment (**nucl-ex** new, recent, search)
- Nuclear Theory (**nucl-th** new, recent, search)
- Physics (**physics** new, recent, search)
  includes: Accelerator Physics; Applied Physics; Atmospheric and Ocean
  Physics; Classical Physics; Computational Physics; Data Analysis, Statis
  of Physics; Instrumentation and Detectors; Medical Physics; Optics; Phy
- Quantum Physics (**quant-ph** new, recent, search)

LT30 Bilbao 2025

30th International Conference on Low Temperature Physics

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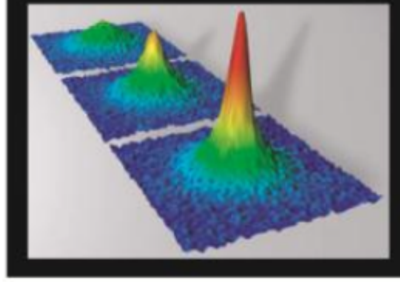
PC1. Quantum gases, fluids and solids.		Invited		Contributed
PC2. Superconductivity.		Invited		Contributed
PC3. Quantum materials – magnetism and topology.		Invited		Contributed
PC4. Nanophysics and quantum transport.		Invited		Contributed
PC5. Quantum information and technologies.		Invited		Contributed
PC6. Cryogenic techniques and applications.		Invited		Contributed



BEC Awards

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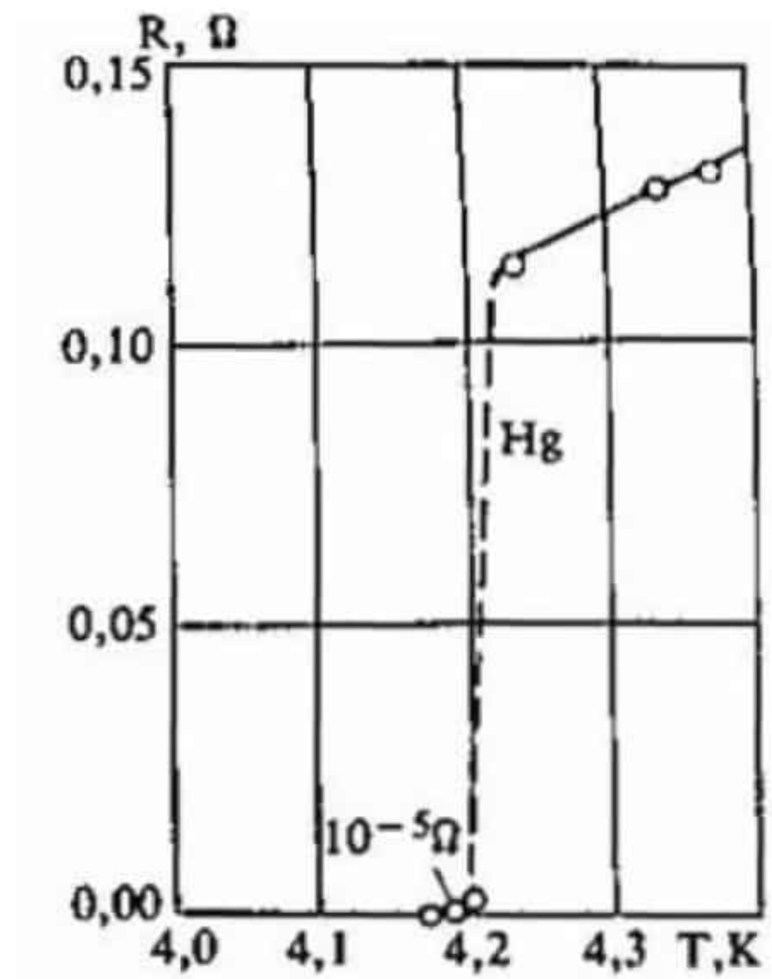
Superflow: persistent mass flow without resistance

Discovery of the zero-resistance by Kamerlingh Onnes (1911)

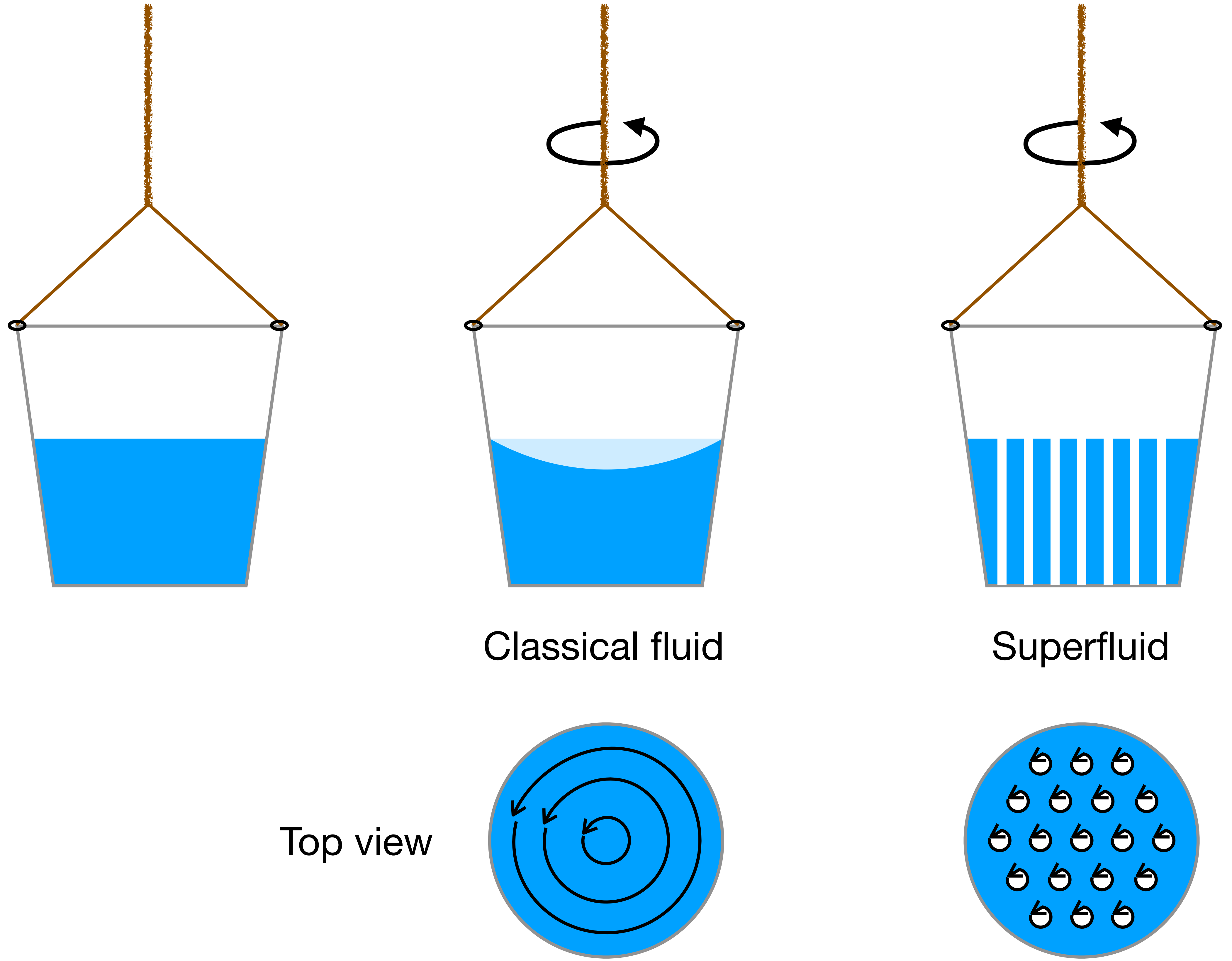
Superfluid of Helium by Kamerlingh Onnes (1938)

Phenomenological explanation by L. Landau J. Phys. (USSR) **5**, 71 (1941).

BCS theory of the superconductor (1957)

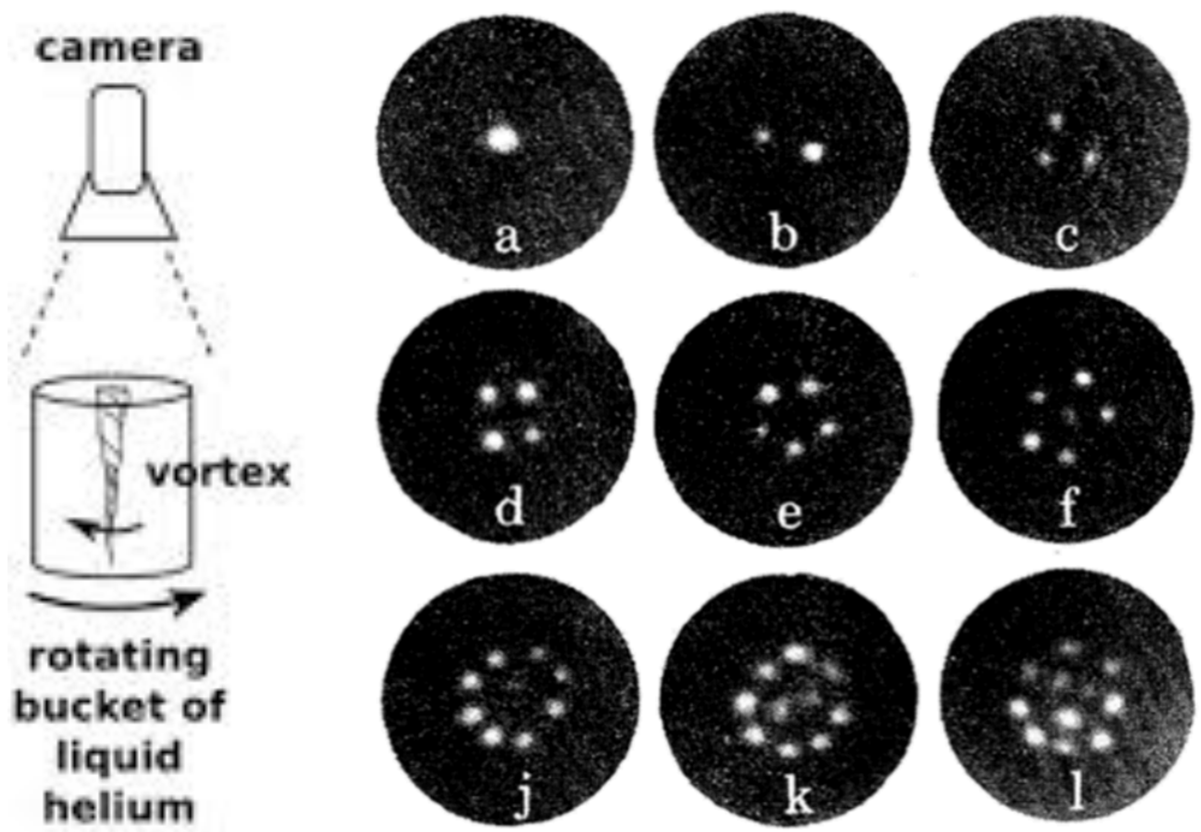


Superfluids of atomic gases



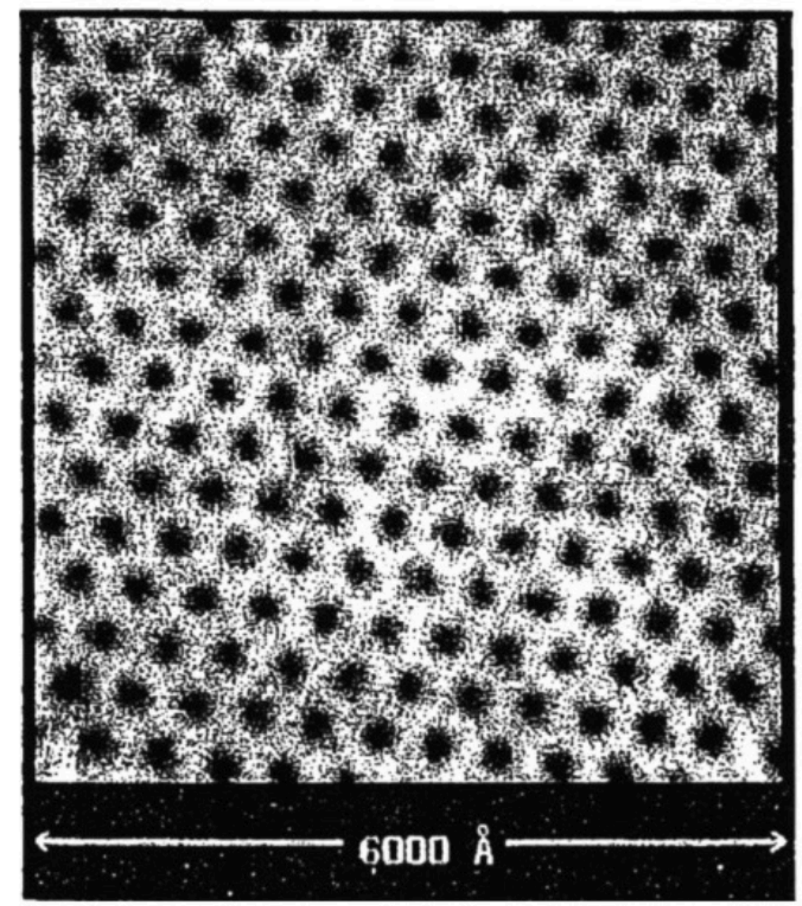
Vortices in quantum fluids

Helium-4



Phys. Rev. Lett. **43,** 214 (1979).

Superconductors



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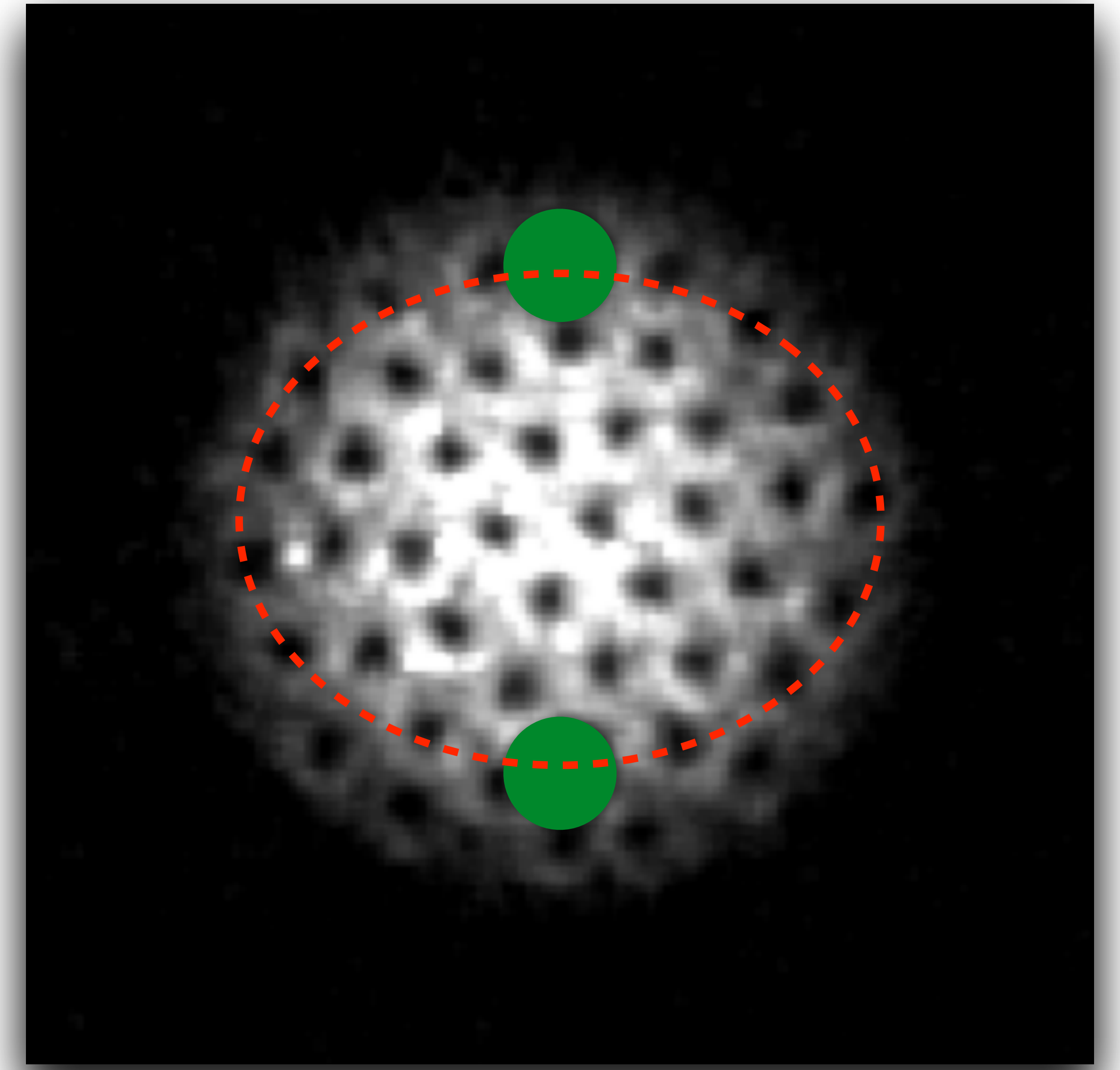
Probing the superfluidity



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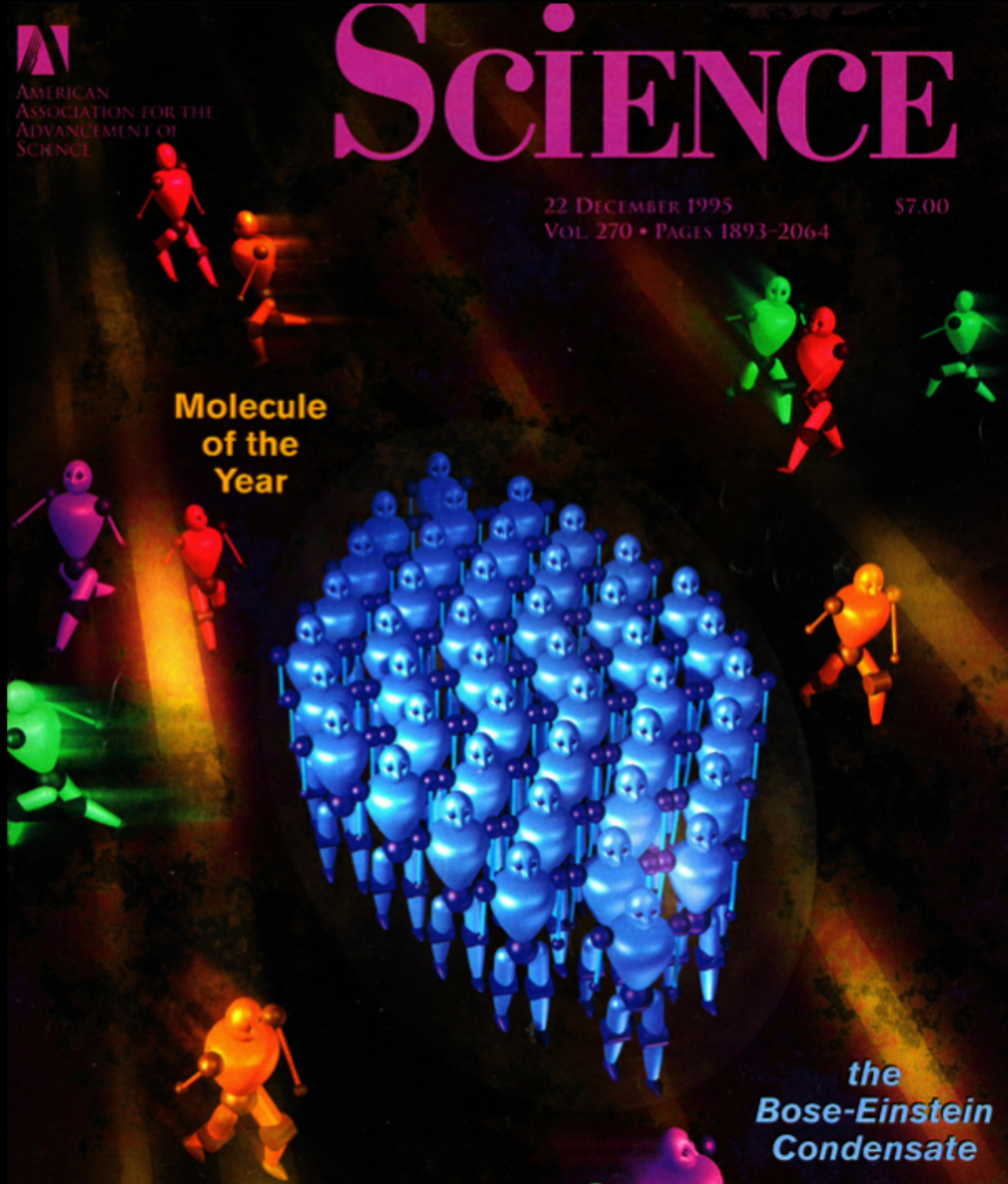
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Science
22 December 1995
Vol. 270 • Pages 1893–2064
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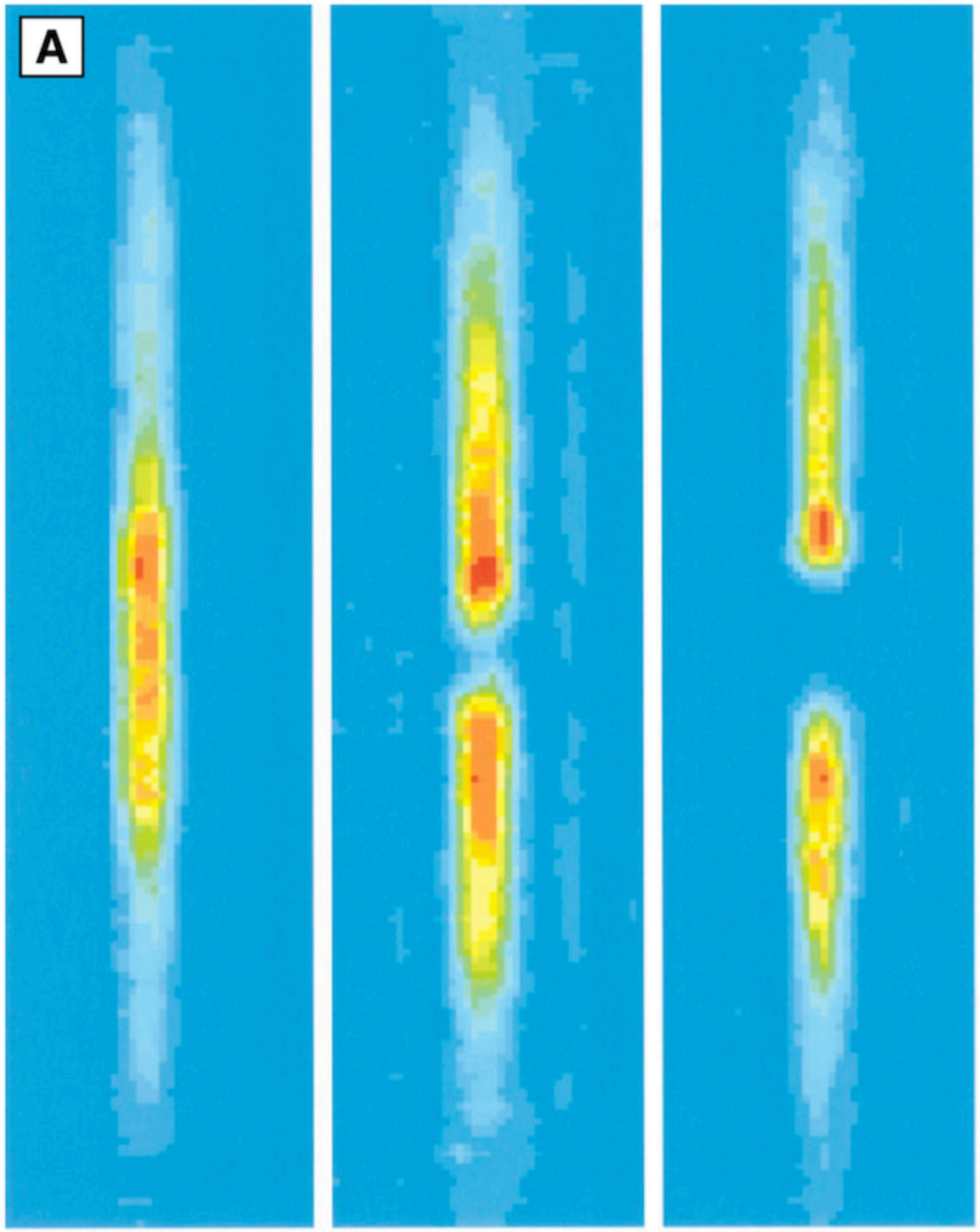
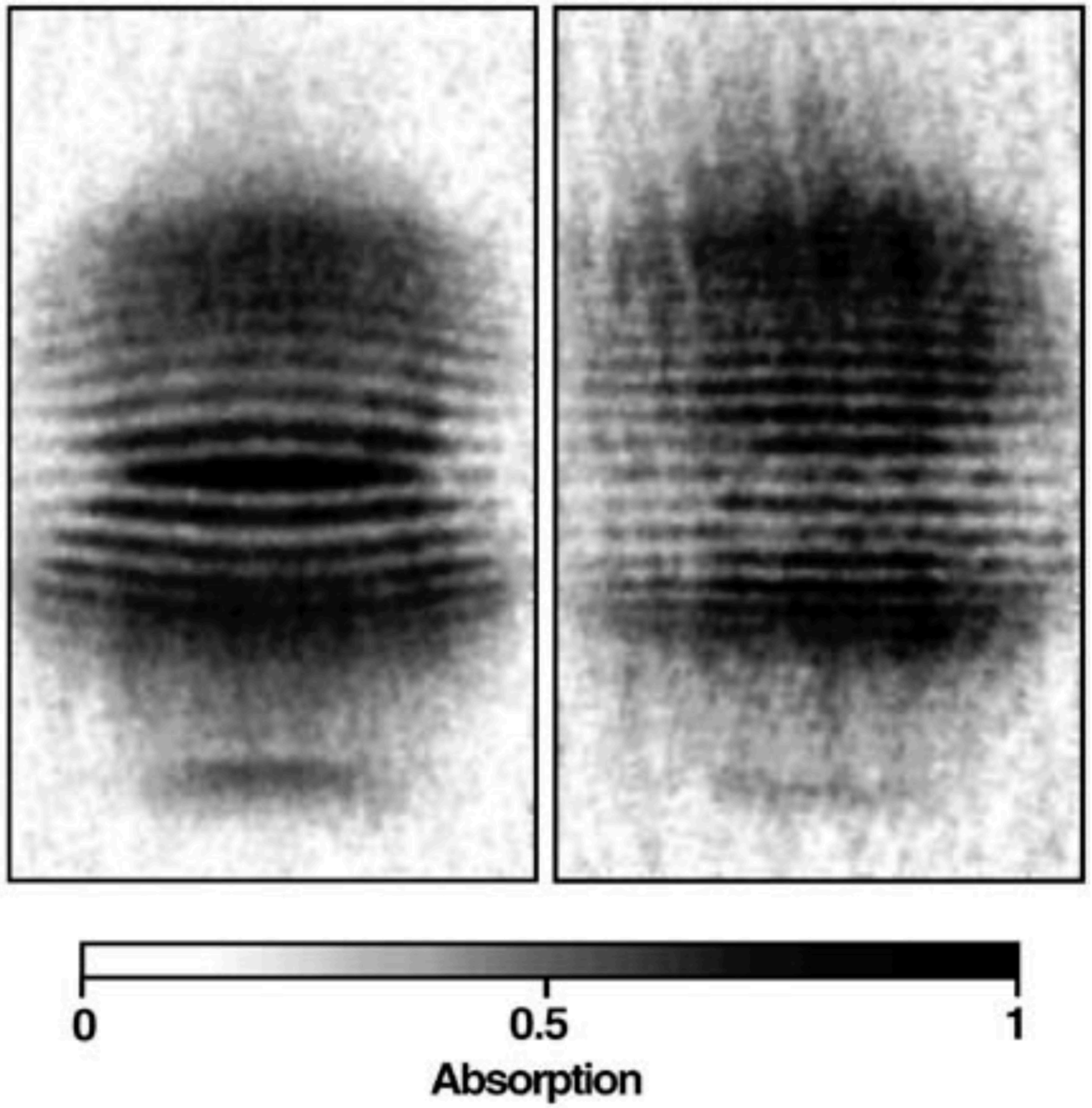
Molecule of the Year
the Bose-Einstein Condensate

Phase coherence of atoms





Interference @ MIT, 1997

Application of atomic BEC

Glimpse idea of what crazy people are doing now

Article

Observation of Bose–Einstein condensates in an Earth-orbiting research lab

https://doi.org/10.1038/s41586-020-2346-1

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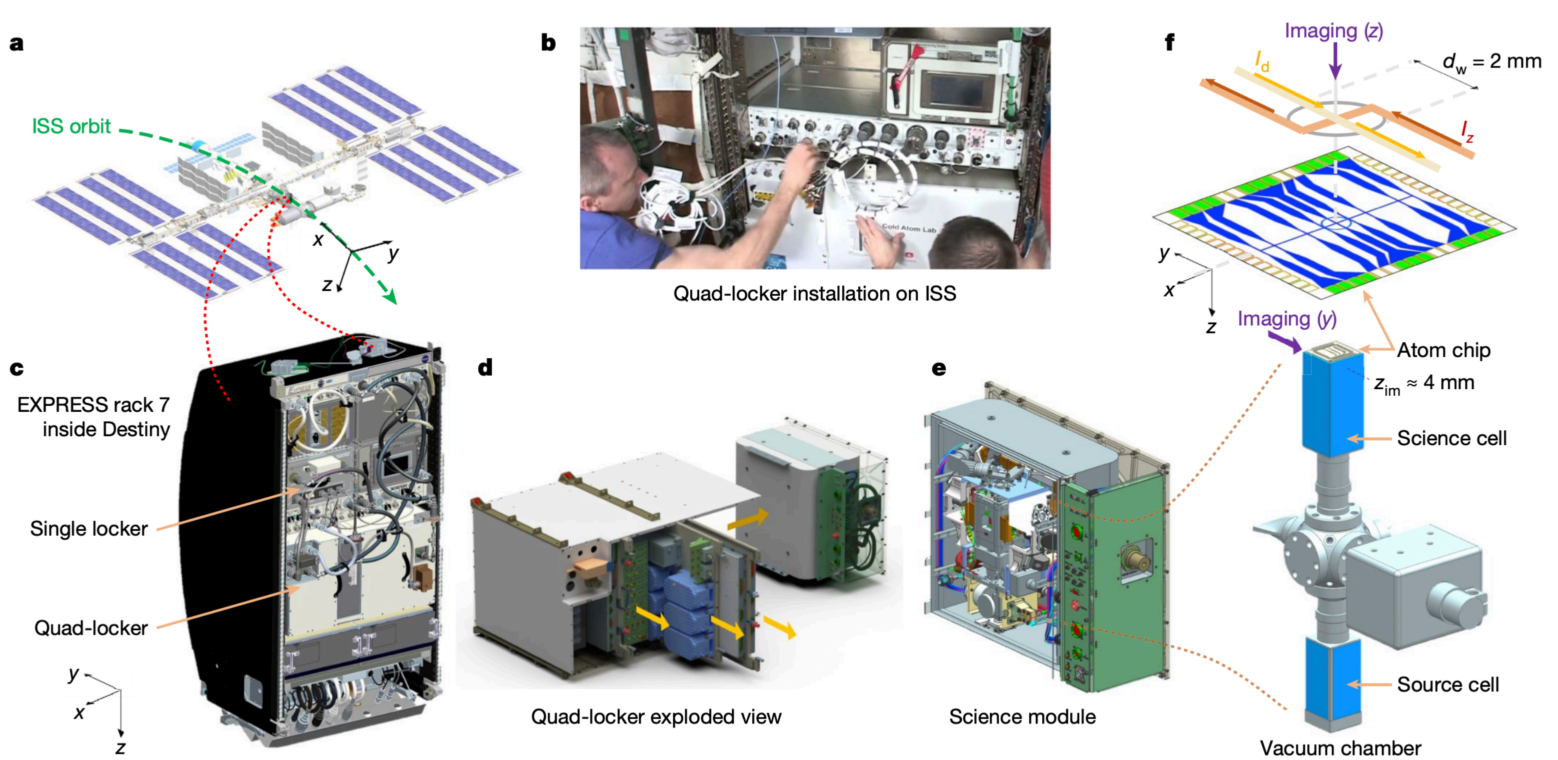
David C. Aveline[1,2]✉, Jason R. Williams[1,2], Ethan R. Elliott[1,2], Chelsea Dutenhoffer[1], James R. Kellogg[1], James M. Kohel[1], Norman E. Lay[1], Kamal Oudrhiri[1], Robert F. Shotwell[1], Nan Yu[1] & Robert J. Thompson[1]✉



Application of atomic BEC

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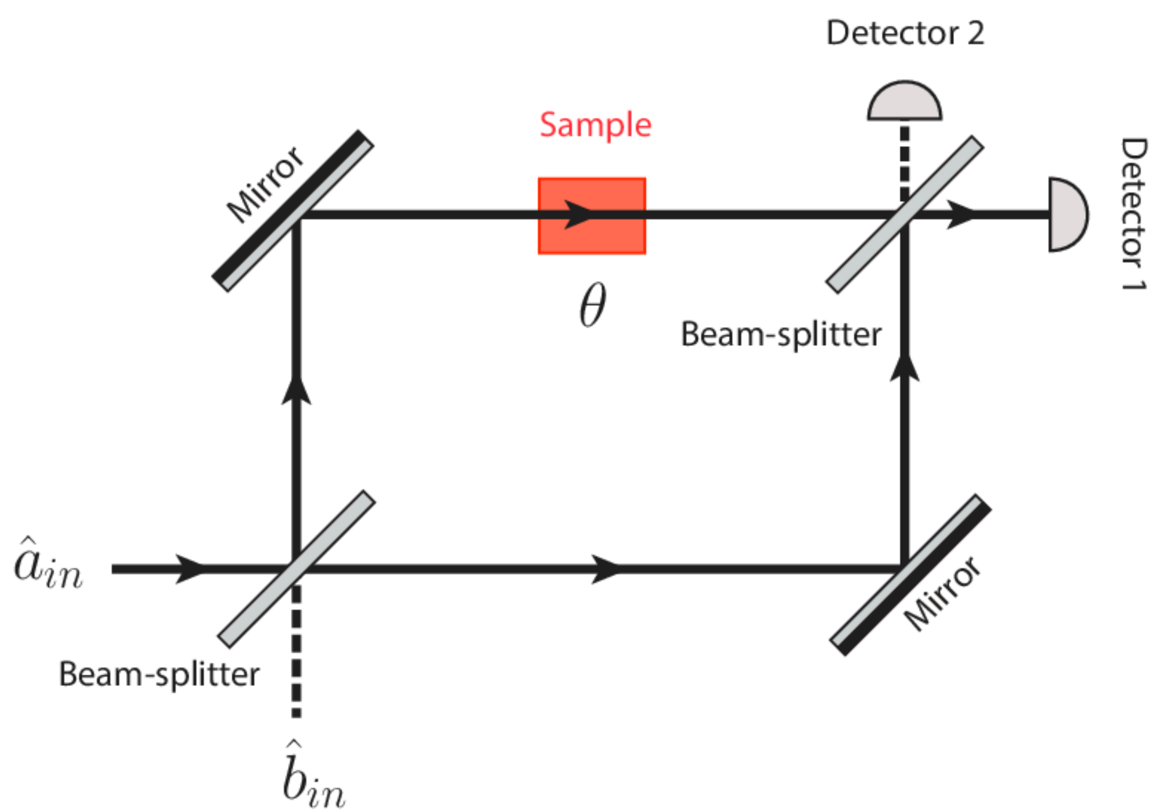
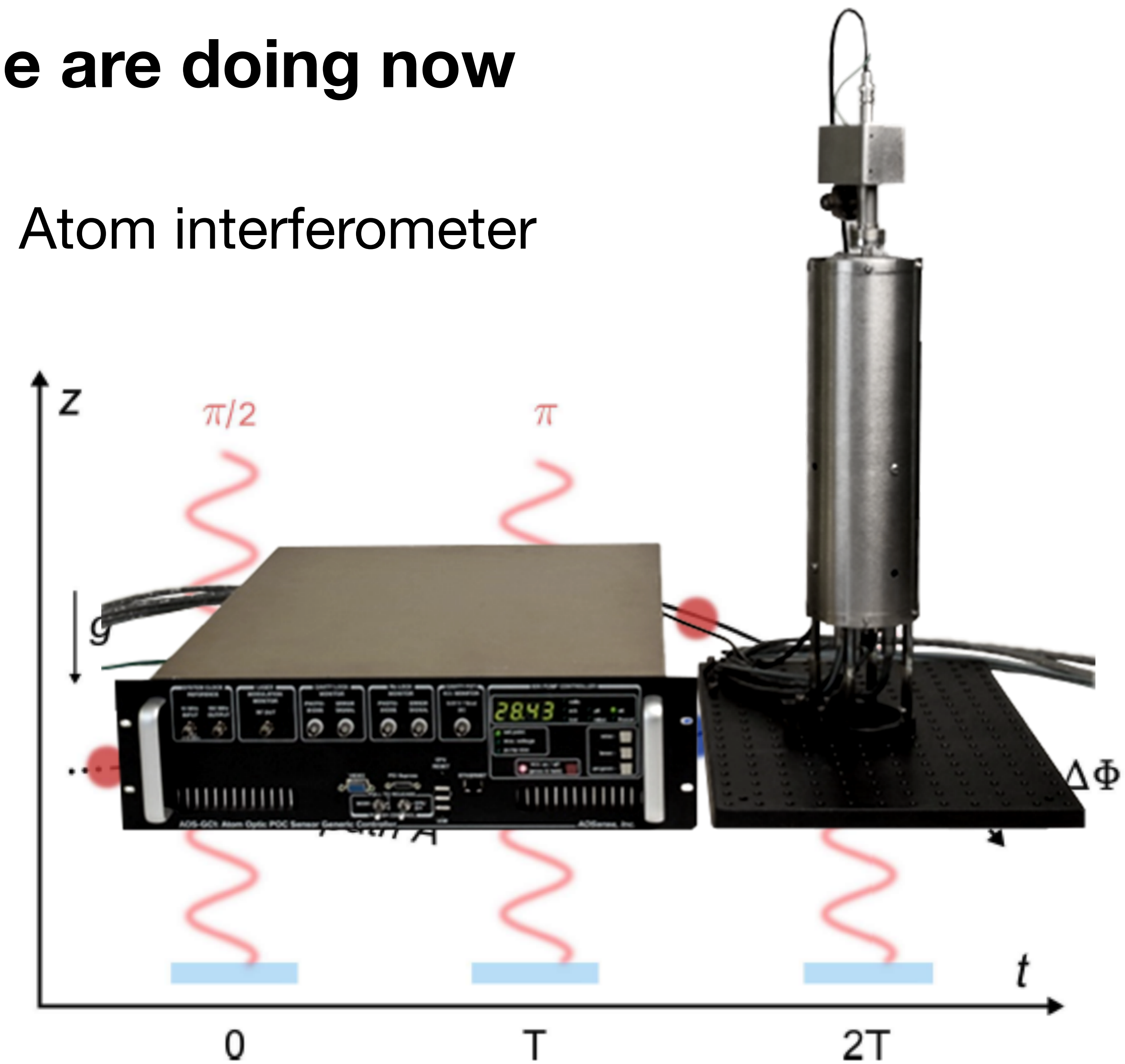
Interferometer in optics

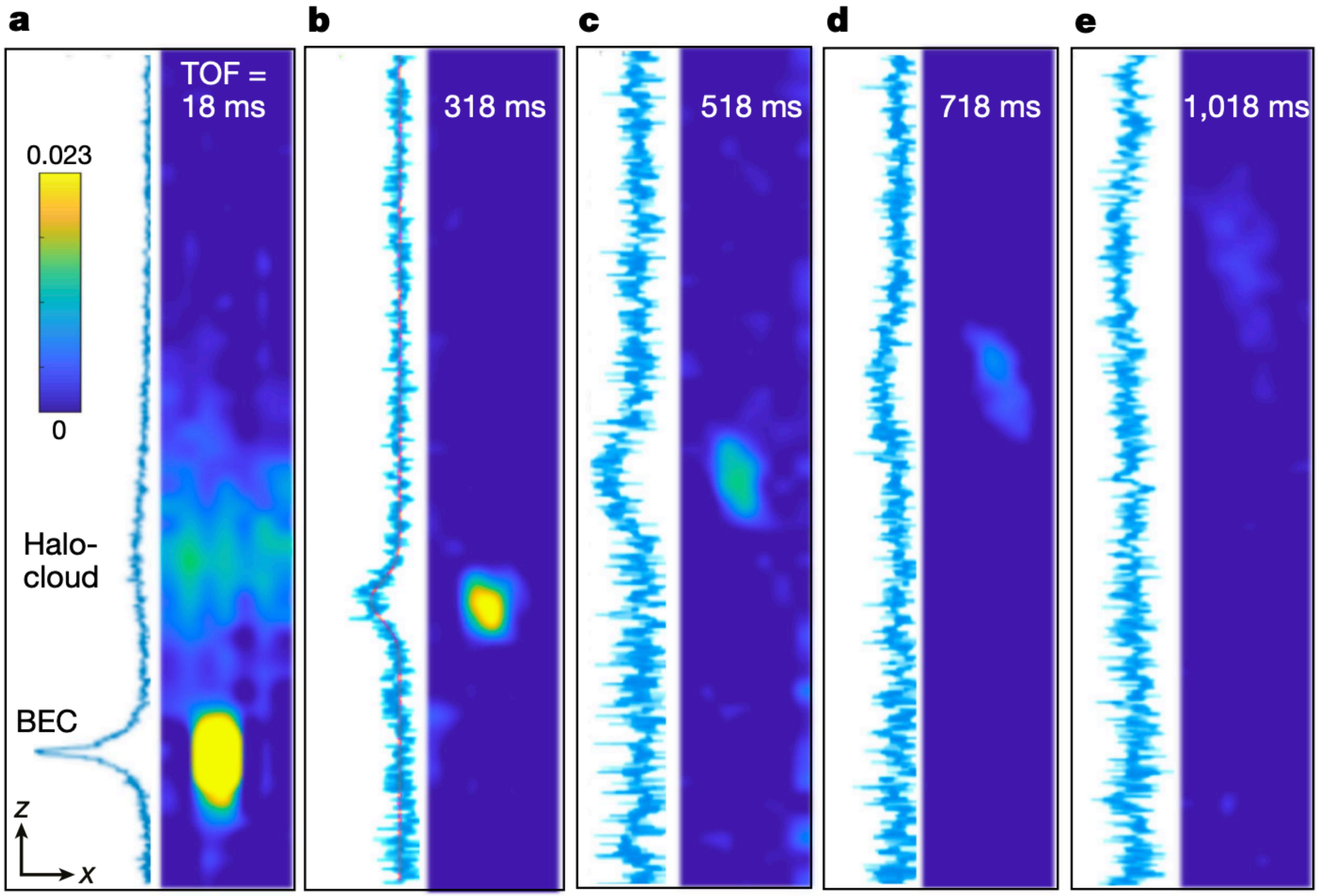


Atom interferometer



Interrogation time (sensitivity) is limited by the expansion time

Expansion of the BEC under micro-gravity



Application of atomic BEC

Glimpse idea of what

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