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8.044 Statistical Physics I
Spring 2008

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1900

1920

1940

1960

1980

2000

70 YEAR QUEST ENDS IN SUCCESS

BOSE-EINSTEIN CONDENSATION

2001 NOBEL PRIZE IN PHYSICS

8.044, LECTURE 33, SPRING 2004

300 K

30 K

3 K

300 mK

30 mK

3 mK

300 μ K

30 μ K

3 μ K

300 nK

30 nK



BOSE-EINSTEIN CONDENSATION IS A QUANTUM MECHANICAL EFFECT

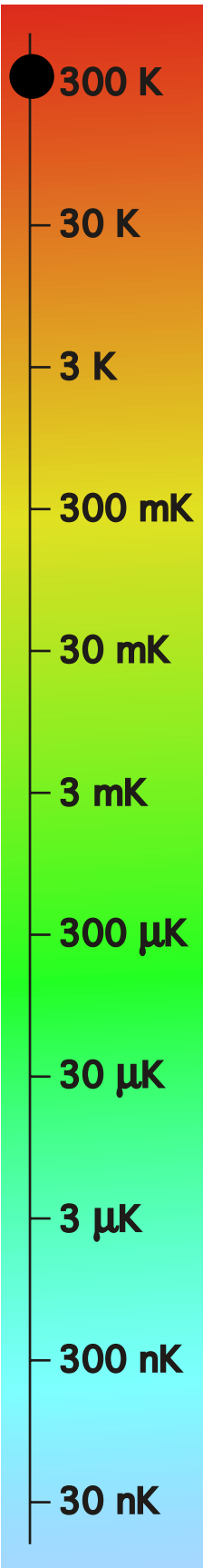


Image removed due to copyright reasons.

Figure 36 from Wright, Orville. *How We Invented the Airplane, An Illustrated History*. New York, NY: Dover, 1988. ISBN: 0486256626.

1900

1920

1940

1960

1980

2000

WITHOUT QUANTUM MECHANICS

Image removed due to copyright reasons.

**WE COULD NOT
BREATHE**

Image removed due to copyright reasons.

**ALL MATTER
WOULD
COLLAPSE**

Image removed due to copyright reasons.

THE SUN WOULD NOT SHINE

300 K

30 K

3 K

300 mK

30 mK

3 mK

300 μ K

30 μ K

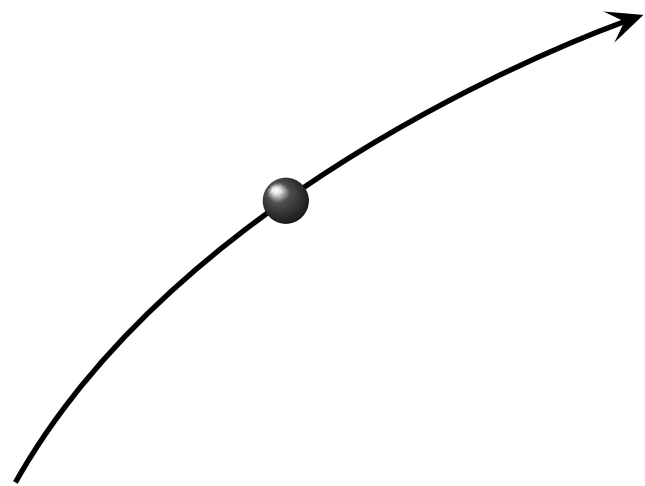
3 μ K

300 nK

30 nK

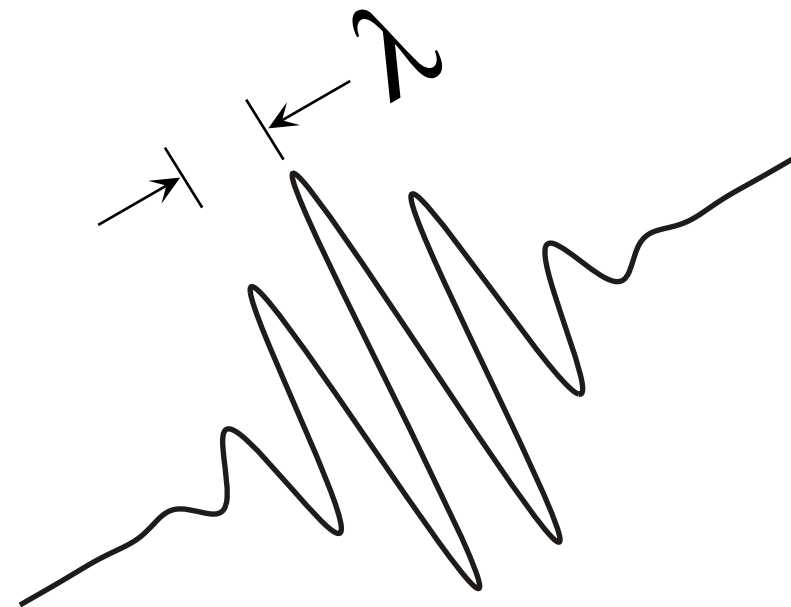


CLASSICAL MODEL



**POINT-LIKE
PARTICLES
FOLLOWING
TRAJECTORIES**

QUANTUM REALITY



**WAVES
PROPAGATING
THROUGH
SPACE**



1900

1920

1940

1960

1980

2000

$$\lambda \propto \frac{1}{m \times v}$$

**FOR ATOMS MOVING AT THERMAL VELOCITY
AT ROOM TEMPERATURE (300K),
 $\lambda <$ THEIR PHYSICAL SIZE.**

**FOR THE ELECTRONS MOVING AROUND THE NUCLEI
IN THOSE ATOMS, $\lambda \approx 1$ ANGSTROM.**

● 300 K

30 K

3 K

300 mK

30 mK

3 mK

300 μ K30 μ K3 μ K

300 nK

30 nK

Image removed due to copyright reasons.

Figure 5-5 from LinkLeighton, Robert B. *LinkPrinciples of modern physics.* New York, NY: McGraw-Hill, 1959.



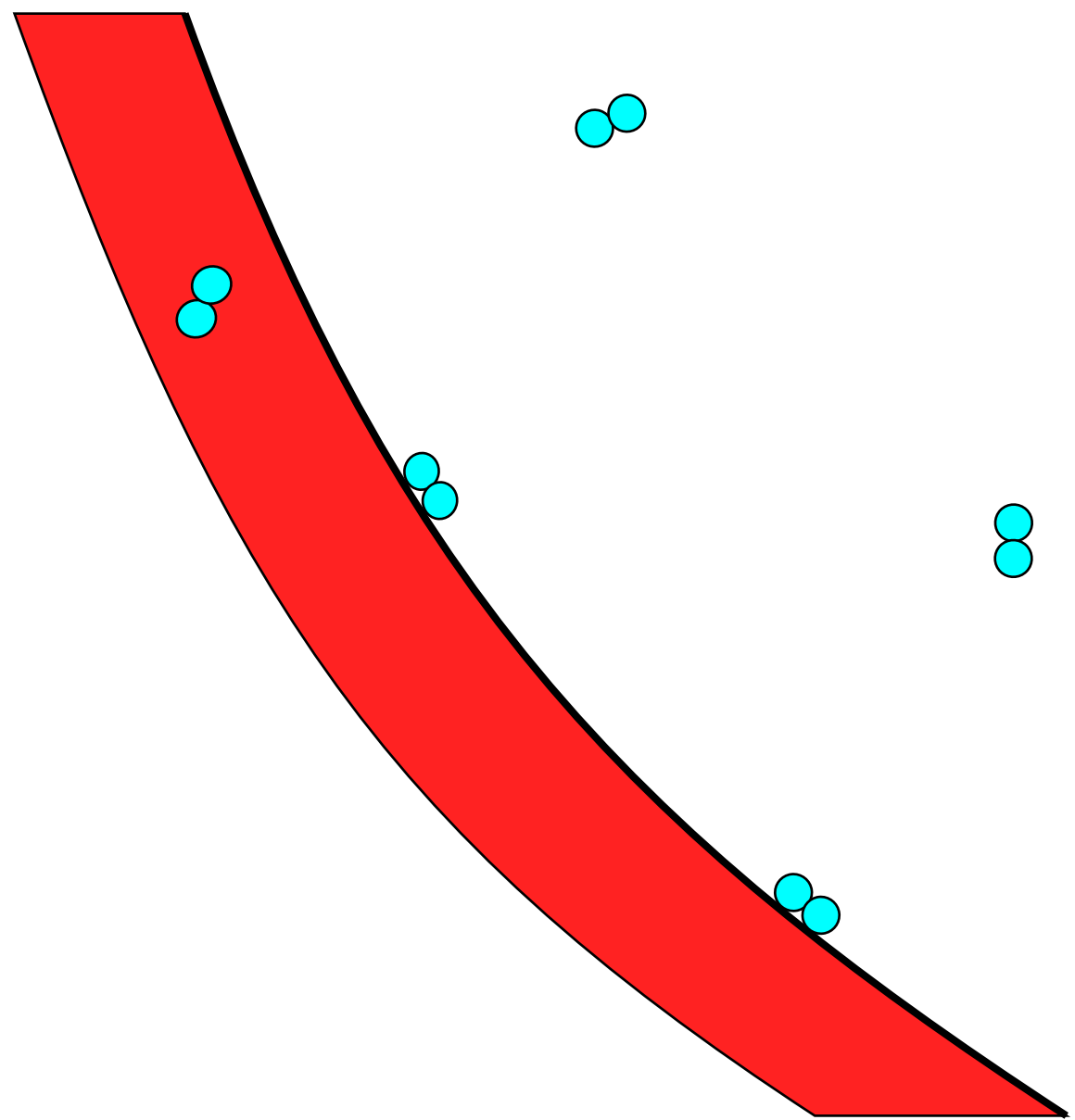
**THE WAVE NATURE OF THE ELECTRONS
STABILIZES THEM AGAINST LOSING ENERGY AND
FALLING INTO THE NUCLEUS.**

Image removed due to copyright reasons.

Figure 3.3 from Kippenhahn, Rudolf. *100 Billion Suns: The Birth, Life, and Death of the Stars*. Princeton, NJ: Princeton University Press, Reprint edition, April 19, 1993, ISBN: 0691087814.

THE WAVE NATURE OF PROTONS ALLOWS THEM TO GET CLOSE ENOUGH DURING COLLISIONS IN THE SUN TO INITIATE FUSION.





QM ALLOWS MOLECULES TO HAVE A STATISTICAL CHANCE OF ADSORBING ON A SURFACE INSTEAD OF REMAINING IN THE BULK GAS



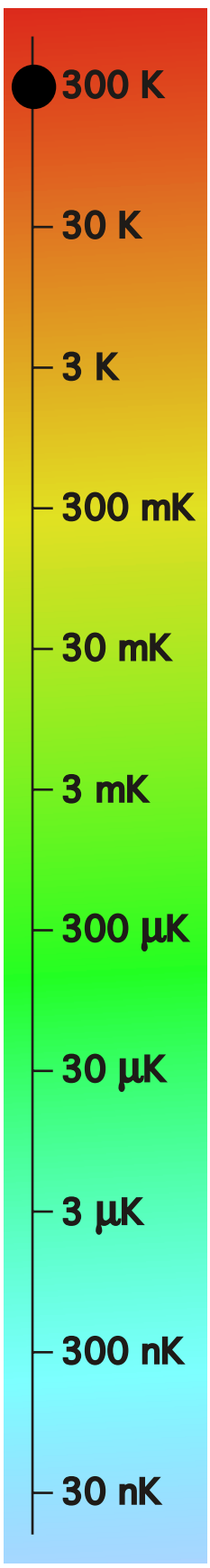
IN 1924 AND 1925 SATYENDRA BOSE AND ALBERT EINSTEIN INVESTIGATED THE INFLUENCE OF QM ON THE COLLECTIVE BEHAVIOR OF PARTICLES.

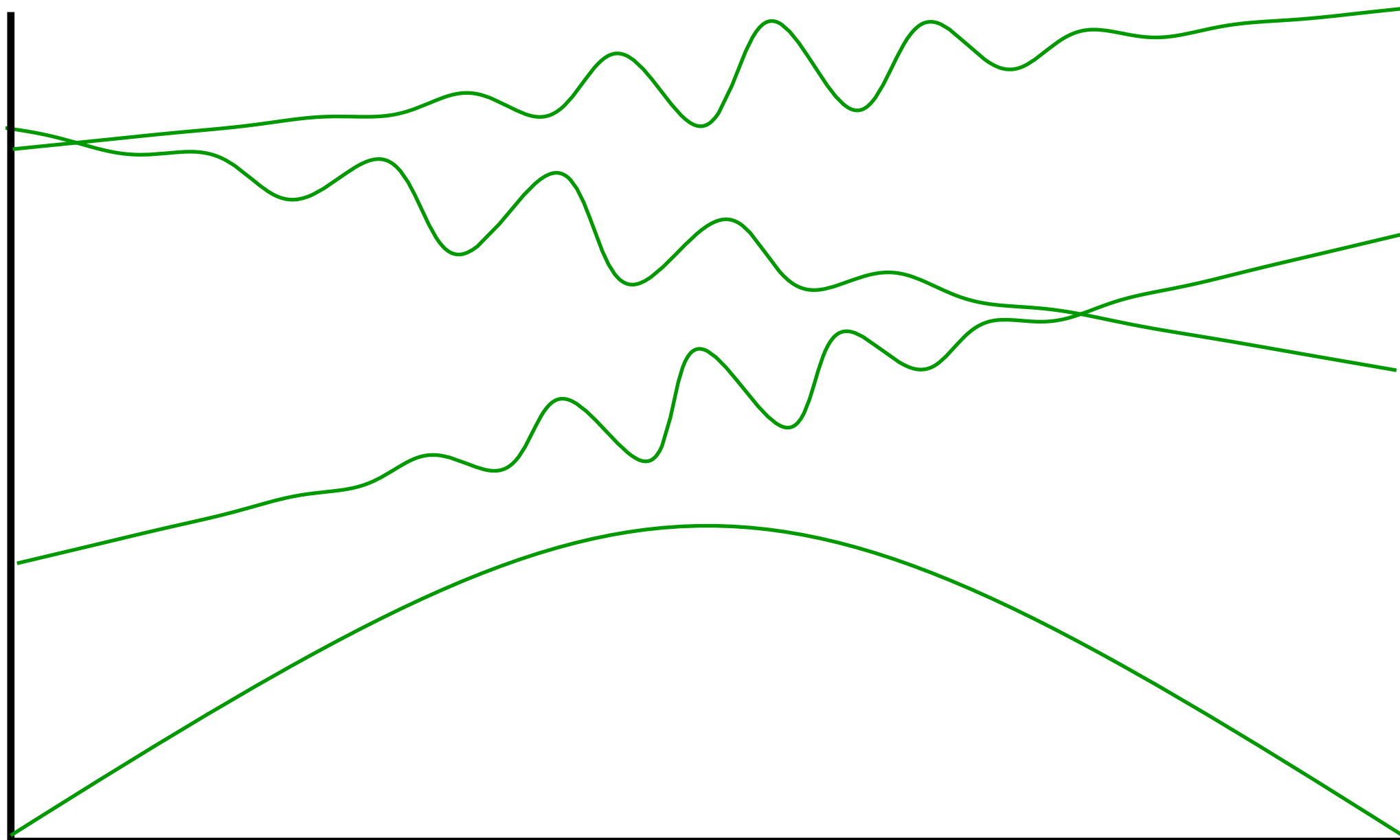
Image of Satyendra Bose removed due to copyright reasons.

Image of Albert Einstein removed due to copyright reasons.

Image of the Nobel prize medal removed due to copyright reasons.

1921
"for his services to Theoretical Physics, and especially for his discovery of the law of the photoelectric effect"





WHEN THE WAVELENGTH BECOMES COMPARABLE TO THE SEPARATION, A PHASE TRANSITION OCCURS. SOME OF THE ATOMS LOSE THEIR IDENTITY AND BECOME PART OF A SINGLE WAVE SPANNING THE CONTAINER.



HALF THE ATOMS IN THE WORLD FOLLOW THE RULES OF BOSE AND EINSTEIN AND ARE CALLED "BOSONS". THE OTHER HALF FOLLOW RULES SET OUT BY ENRICO FERMI AND PAUL DIRAC AND ARE CALLED "FERMIONS".

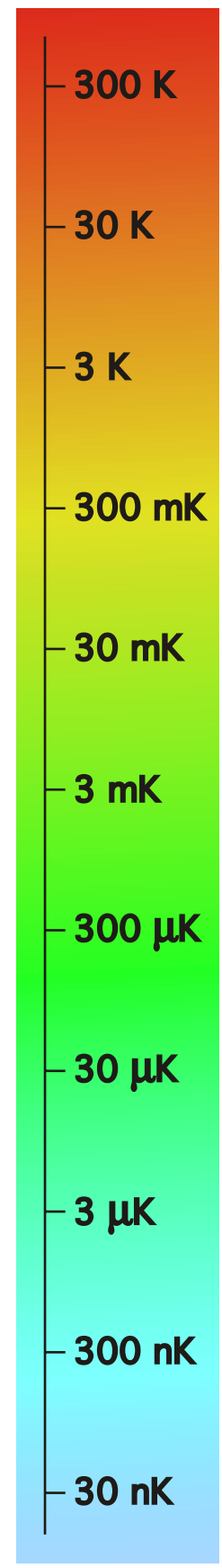


Image of Enrico Fermi removed due to copyright reasons.

Image of Paul Dirac removed due to copyright reasons.

Image of the Nobel Prize medal removed due to copyright reasons.

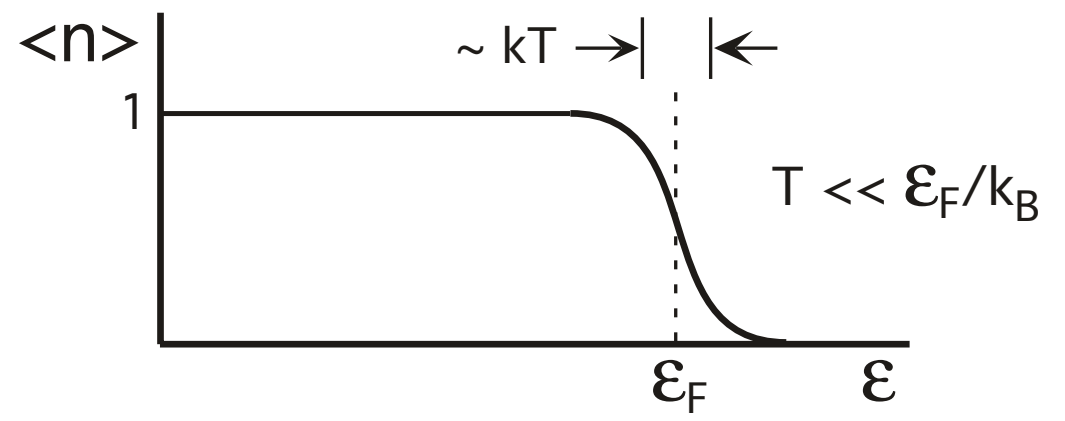
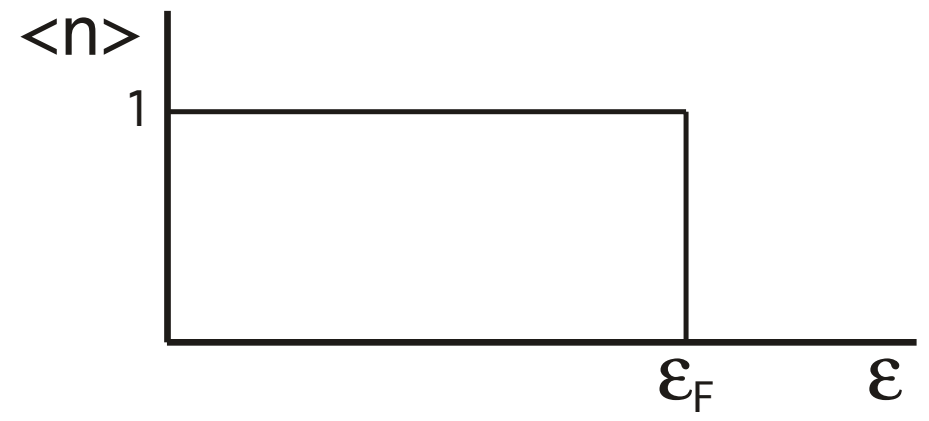
Image of the Nobel Prize medal removed due to copyright reasons.



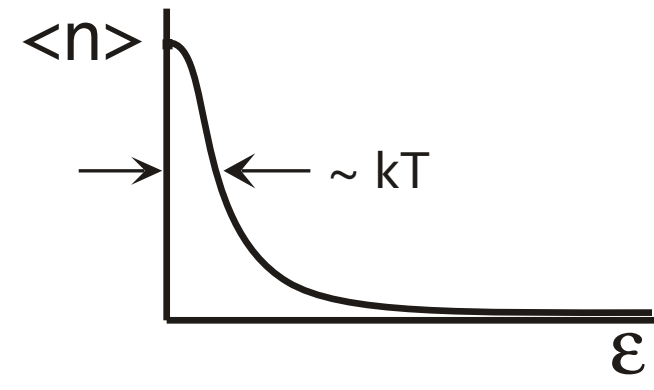
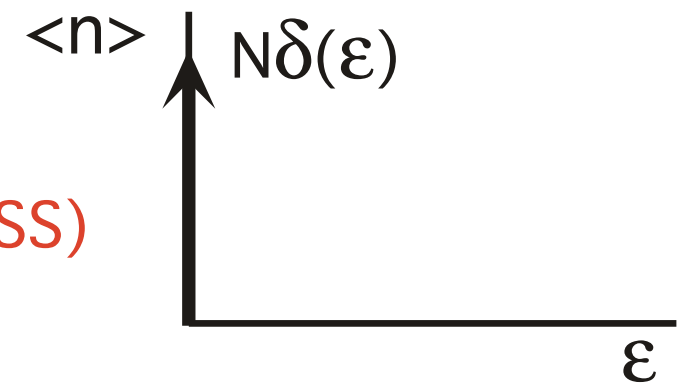
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FINITE T

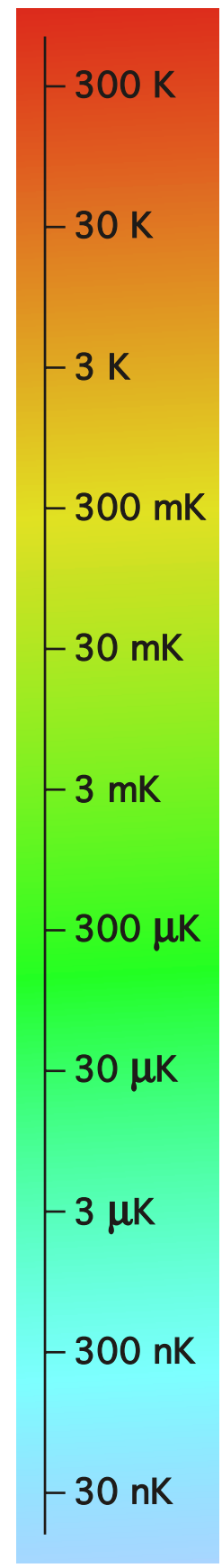
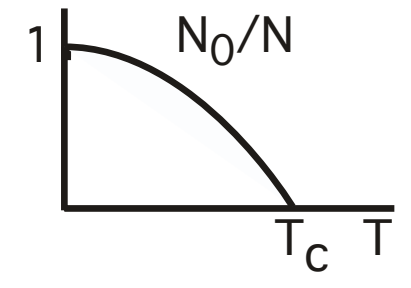
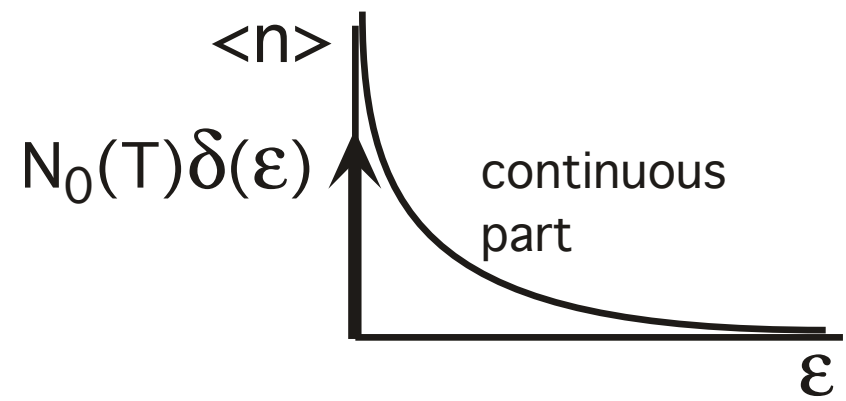
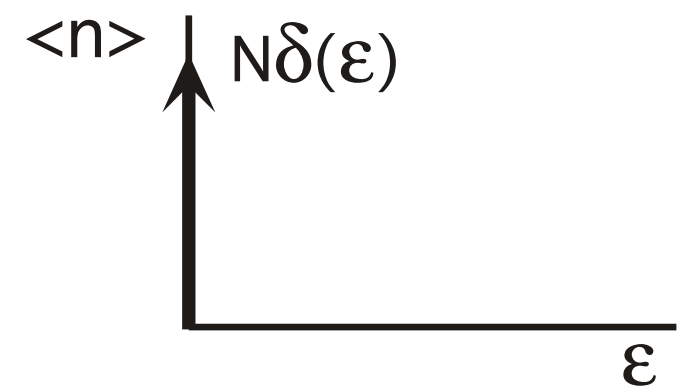
FERMI



**BOSE
(GOOD GUESS)**



**BOSE
(ACTUAL)**



1900

1920

1940

1960

1980

2000

O₂ LIQUEFIES AT 90K

O₂ FREEZES AT 50K

H₂ LIQUEFIES AT 20K

H₂ FREEZES AT 14K

He LIQUEFIES AT 4K

300 K

30 K

3 K

300 mK

30 mK

3 mK

300 μ K

30 μ K

3 μ K

300 nK

30 nK

REAL ATOMS OR MOLECULES DO INTERACT WITH EACH OTHER AND UNDERGO LIQUEFICATION AND FREEZING DUE TO THESE INTERACTIONS.



SUPERCONDUCTIVITY WAS DISCOVERED BY KAMERLINGH ONNES IN 1911.

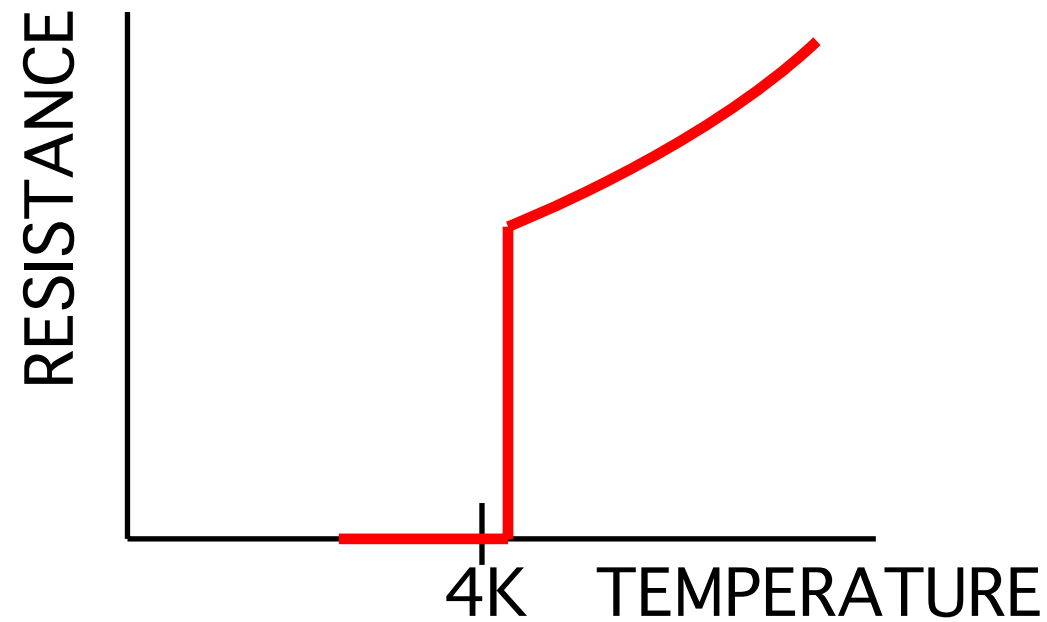


Image of Kamerlingh Onnes removed due to copyright reasons.

Image of the Nobel Prize medal removed due to copyright reasons.

1913
"for his investigations on the properties of matter at low temperatures which led, inter alia, to the production of liquid helium"





The Nobel Prize in Physics 1972

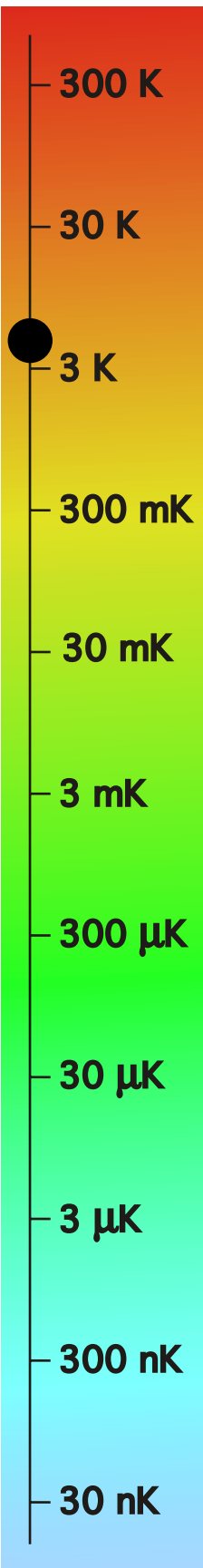
Image of the Nobel Prize medal removed due to copyright reasons.

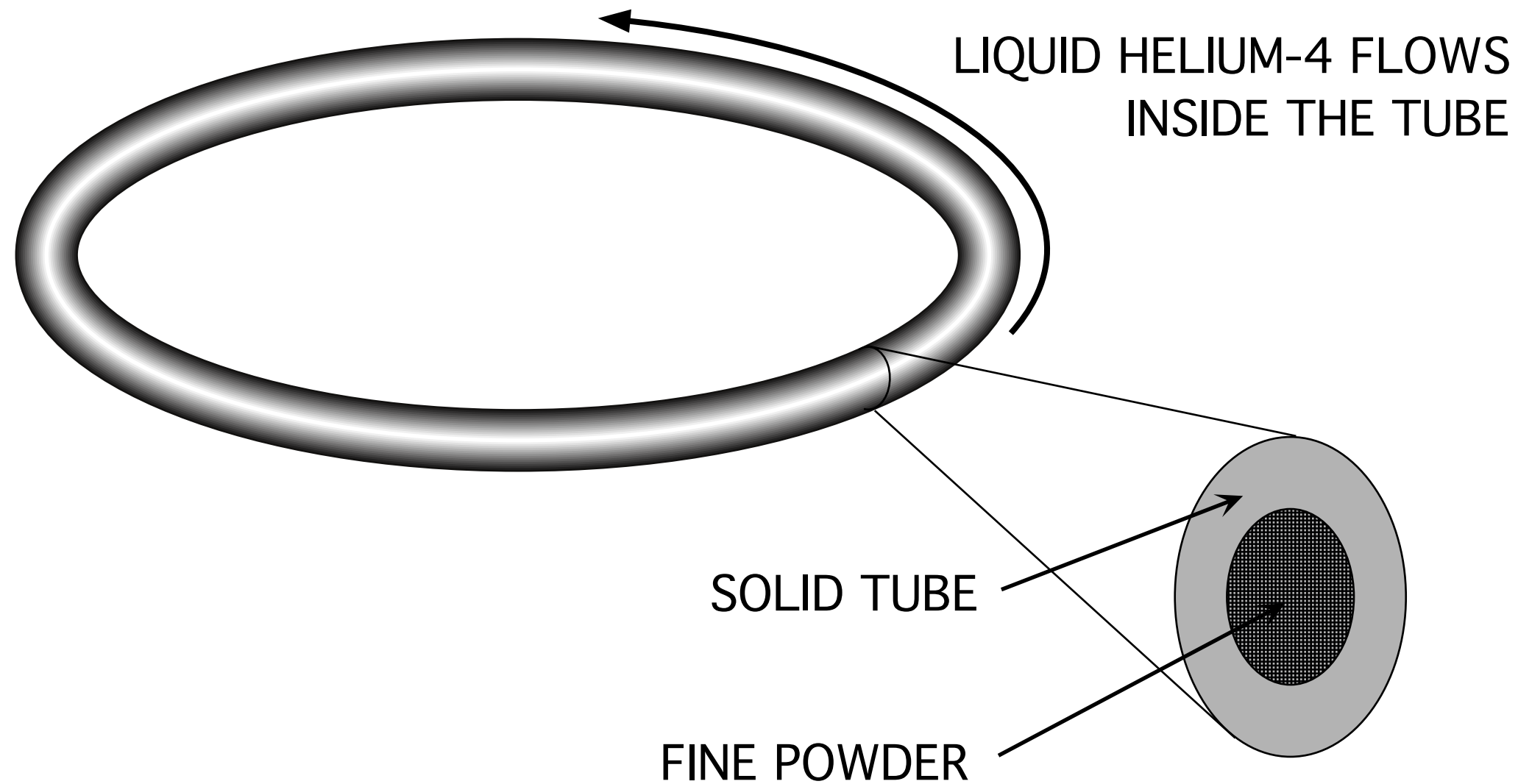
"for their jointly developed theory of superconductivity, usually called the BCS-theory"

Image of John Bardeen removed due to copyright reasons.

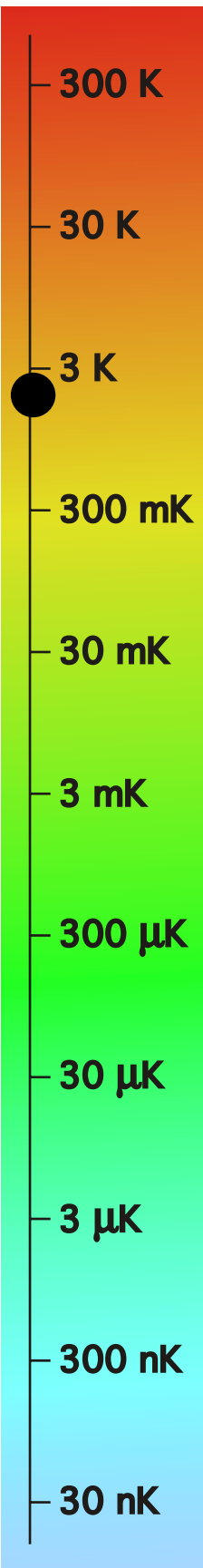
Image of Leon Neil Cooper removed due to copyright reasons.

Image of John Robert Schrieffer removed due to copyright reasons.





SUPERFLUIDITY WAS DISCOVERED IN HELIUM-4 IN THE 1930s AT A TEMPERATURE OF 2 KELVIN.





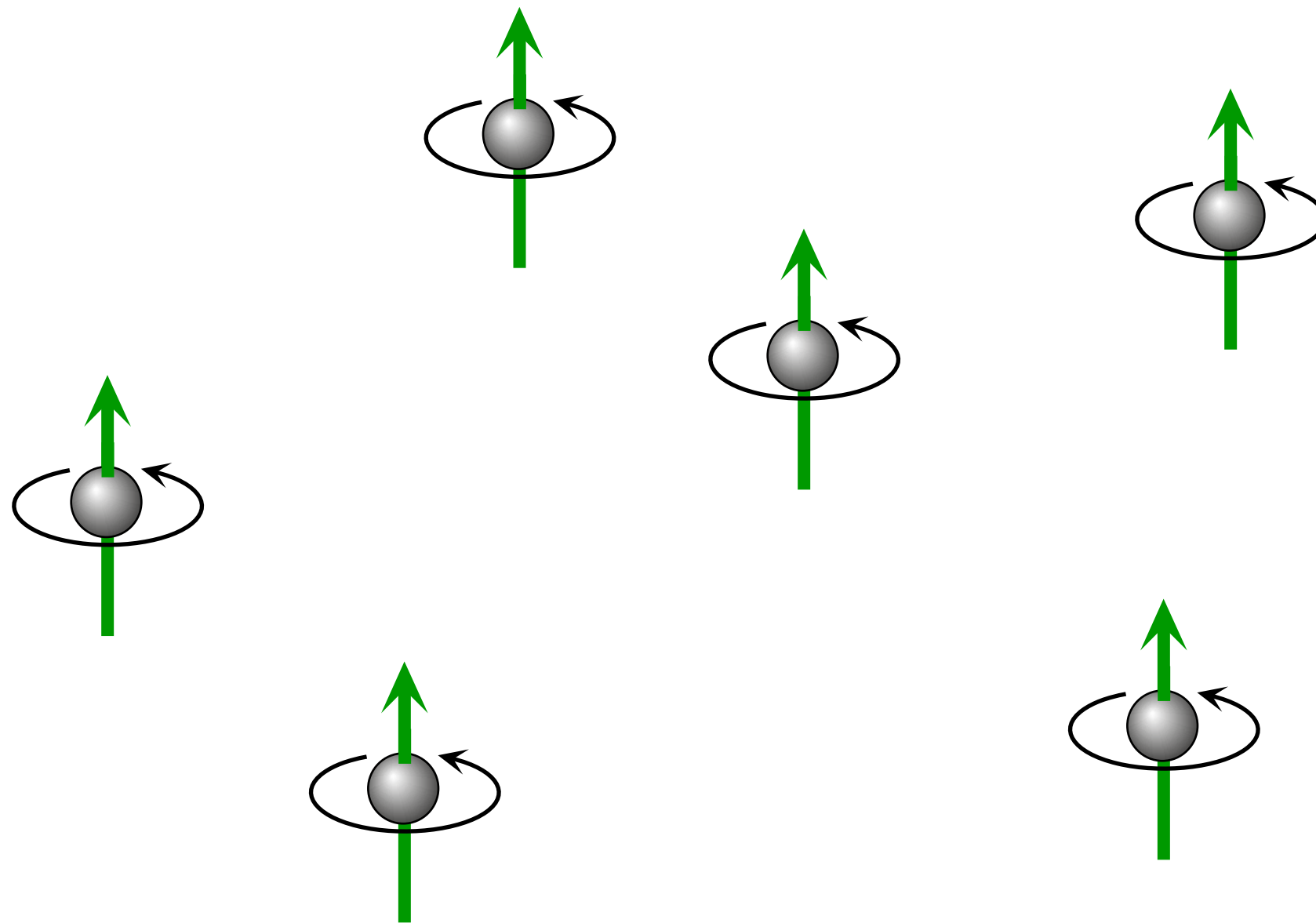
The Nobel Prize in Physics 1996

"for their discovery of superfluidity in helium-3"

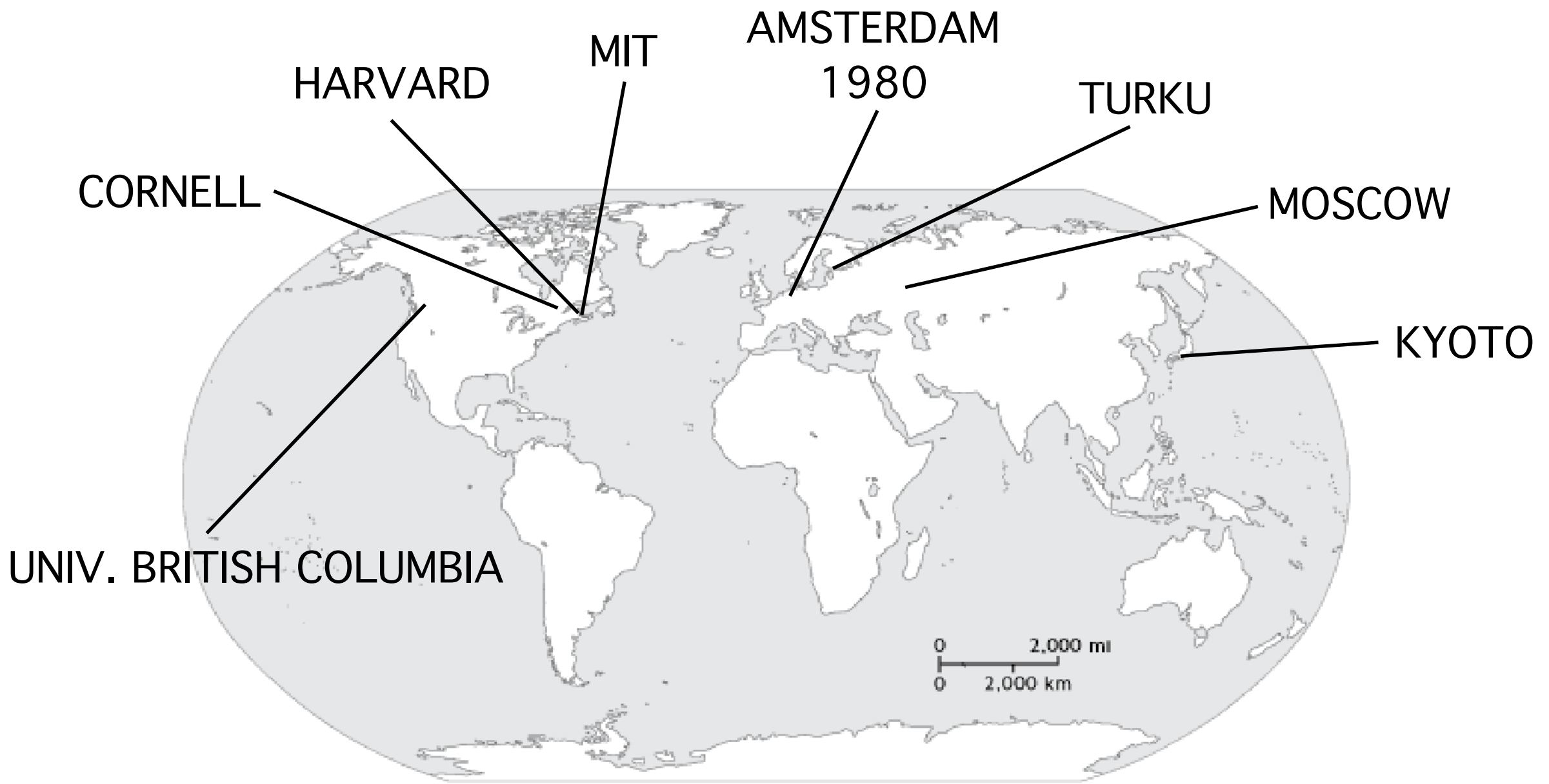
Image of the Nobel Prize winners David M. Lee, Douglas D. Osheroff, and Robert C. Richardson removed due to copyright reasons.

SUPERFLUIDITY WAS DISCOVERED IN HELIUM-3 IN 1972 AT A TEMPERATURE OF 2 MILLIKELVIN.

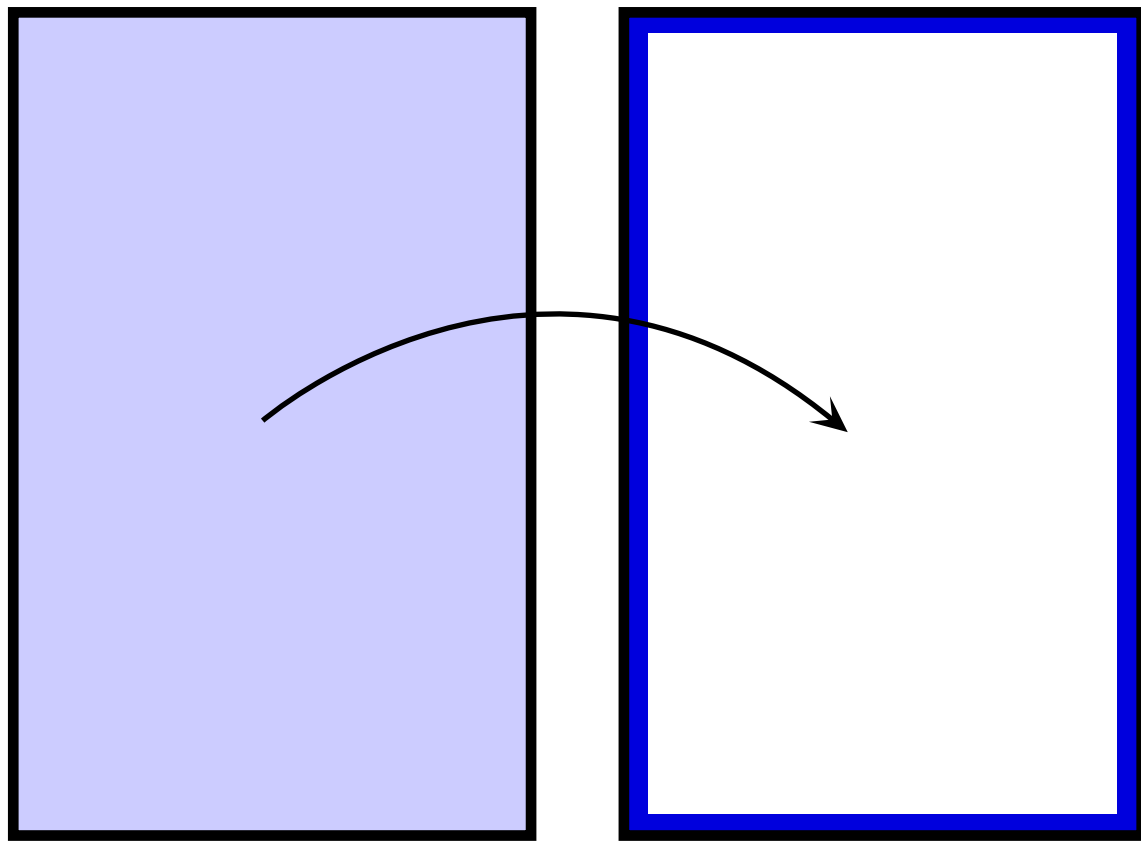




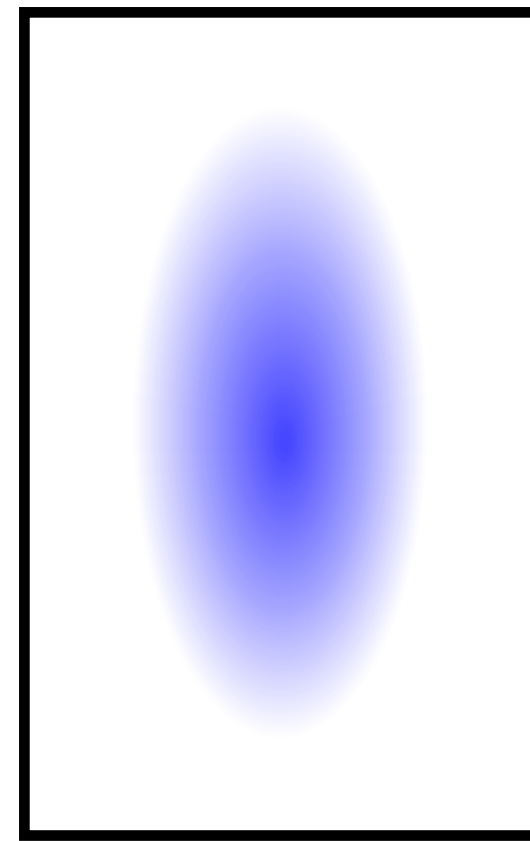
ATOMIC HYDROGEN WILL REMAIN A GAS DOWN TO ABSOLUTE ZERO IF ITS MAGNETIC MOMENTS ARE ALIGNED BY A MAGNETIC FIELD.



GROUPS WORKING ON SPIN-POLARIZED ATOMIC HYDROGEN



CONFINEMENT BY WALLS

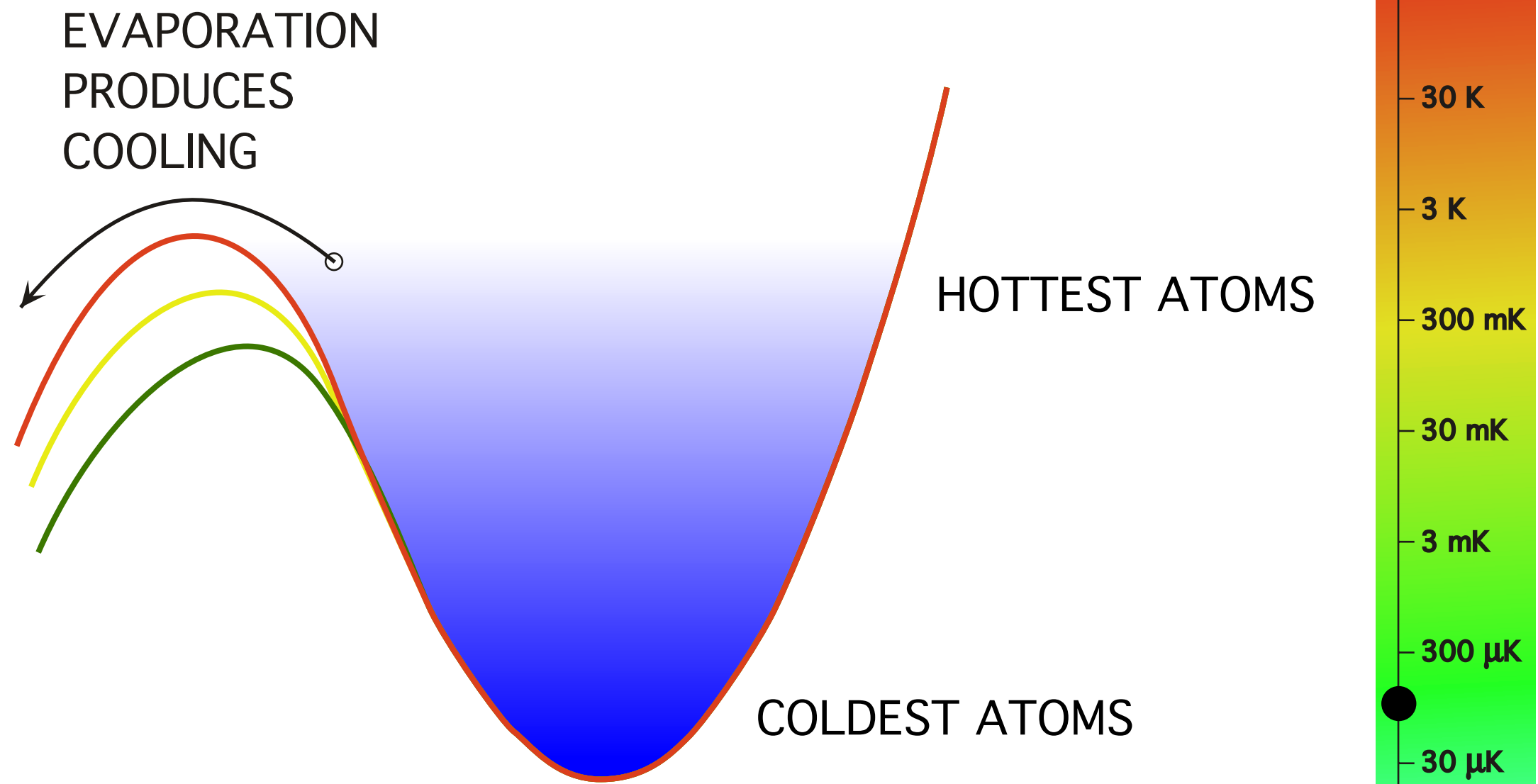


TRAPPING BY A MAGNETIC FIELD

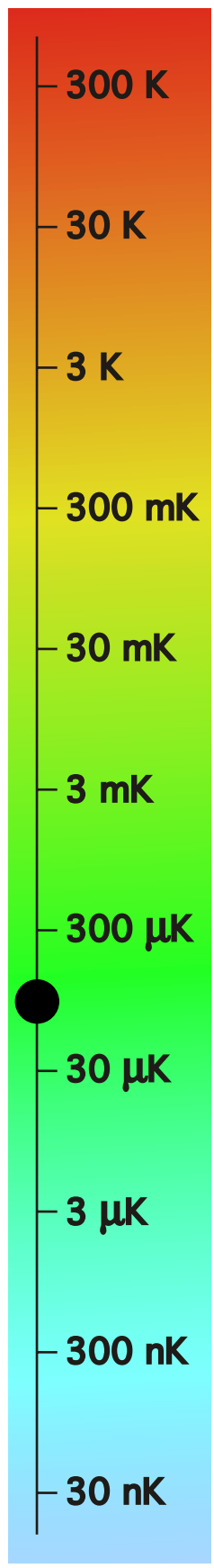
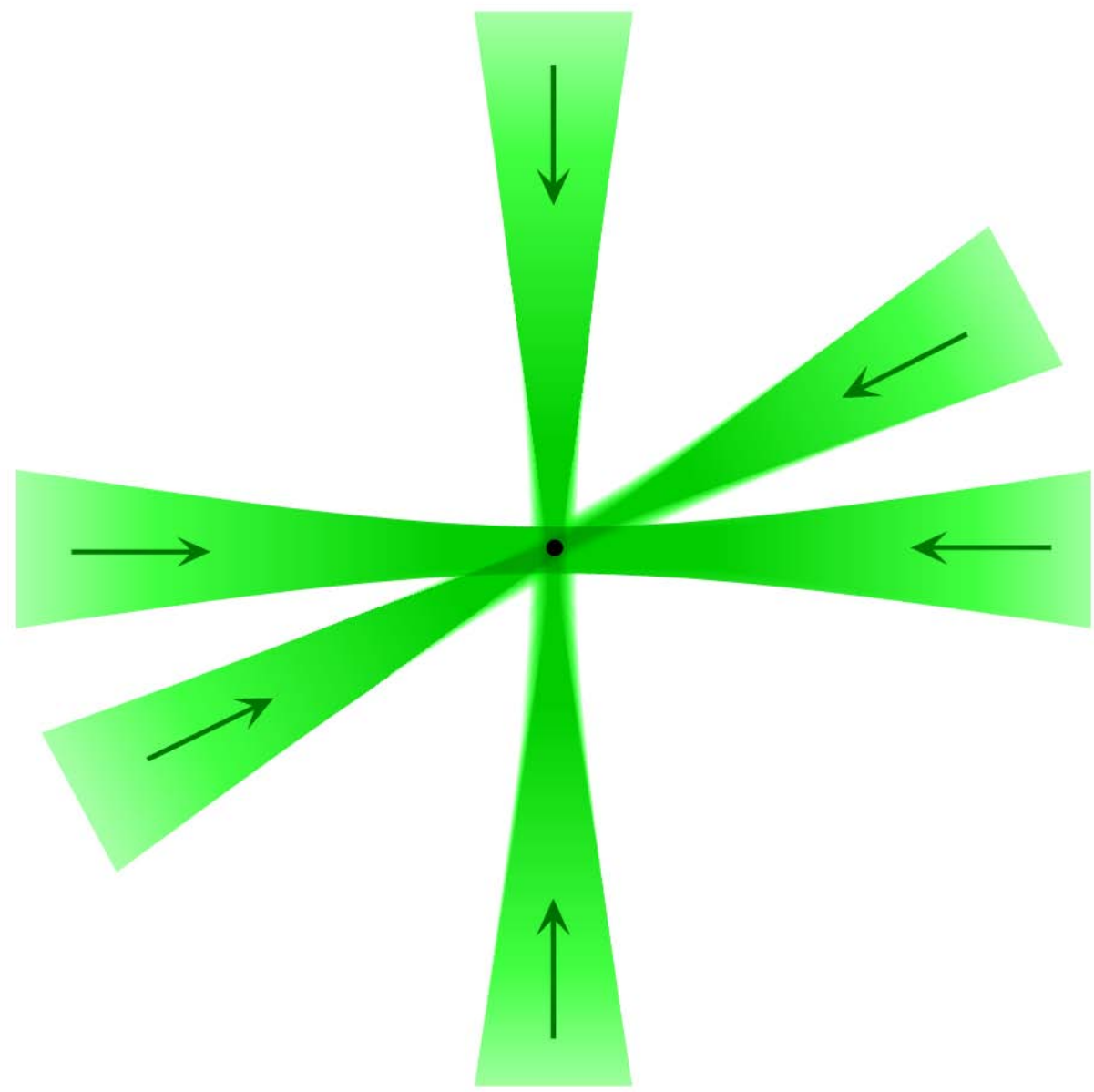
WALLS CAUSE THE MOMENTS TO FLIP; THEN THE ATOMS RECOMBINE INTO MOLECULES AND FREEZE OUT.

A MAGNETIC TRAP KEEPS THE ATOMS OFF THE WALLS.





IN 1986 HARALD HESS, A POSTDOCTORAL FELLOW IN MIT'S HYDROGEN GROUP, PROPOSES MAGNETIC TRAPPING AND EVAPORATIVE COOLING.



BEGINNING IN THE 1980s, METHODS WERE DEVELOPED TO COOL ATOMS INTO THE MICROKELVIN REGION OF TEMPERATURES USING LASERS.



Image of the Nobel Prize medal removed due to copyright reasons.

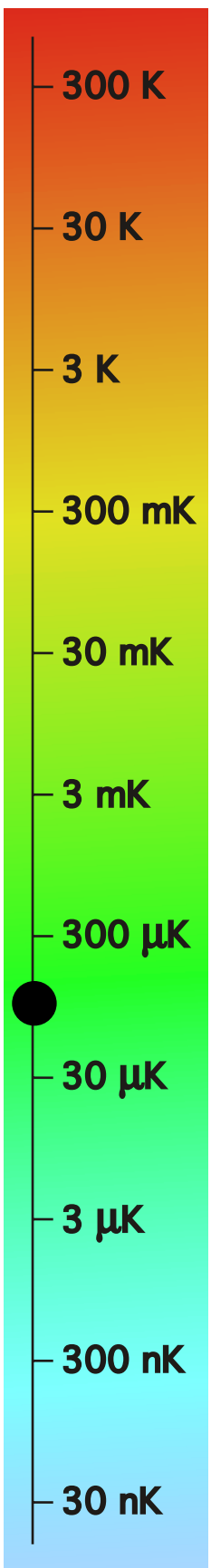
The Nobel Prize in Physics 1997

"for development of methods to cool and trap atoms with laser light"

Image of Steven Chu removed due to copyright reasons.

Image of Claude Cohen-Tannoudhi removed due to copyright reasons.

Image of William Phillips removed due to copyright reasons.



1900

1920

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1960

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2000

LASER COOLING WORKS BEST WITH CERTAIN ATOMS SUCH AS LITHIUM (Li), SODIUM (Na), and RUBIDIUM (Rb).

BUT LASER COOLING ALONE CAN NOT GET THESE ATOMS COLD ENOUGH TO ACHIEVE BEC.

FOR THE FINAL STAGE OF COOLING ONE MUST TURN TO EVAPORATIVE COOLING.

THEN THE RACE BEGAN: LOWER THE TEMPERATURE WHILE INCREASING THE DENSITY.

300 K

30 K

3 K

300 mK

30 mK

3 mK

300 μ K

30 μ K

3 μ K

300 nK

30 nK



ERIC CORNELL & CARL WIEMAN
JILA (NIST AND UNIV. OF COLORADO)
Rb

Image removed due to copyright reasons.

Image removed due to copyright reasons.

RANDALL HULET
RICE UNIVERSITY
Li

WOLFGANG KETTERLE
MIT
Na

Image removed due to copyright reasons.

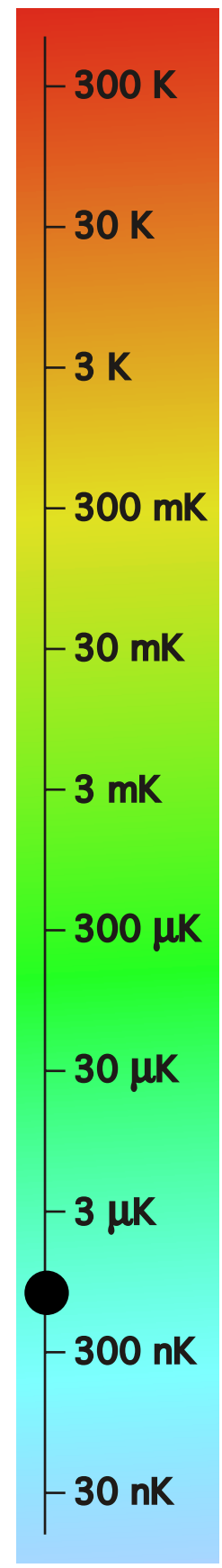




Image of Dan Kleppner, Tom Greytak, Wolfgang Ketterle, and Dave Pritchard removed due to copyright reasons.

DAN KLEPPNER

WOLFGANG KETTERLE

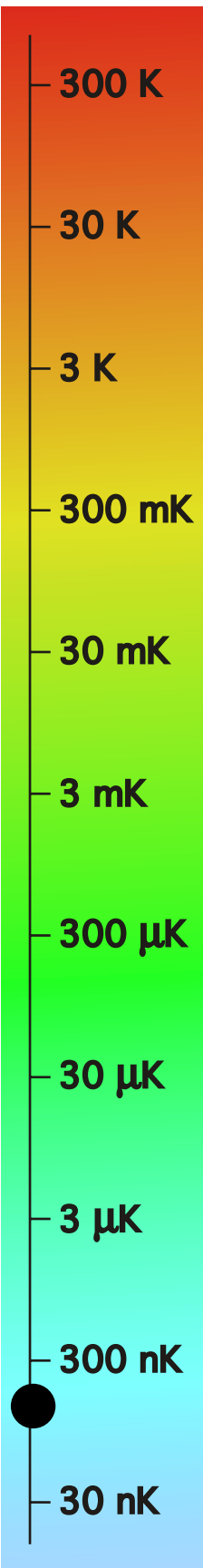
TOM GREYTAK

DAVE PRITCHARD

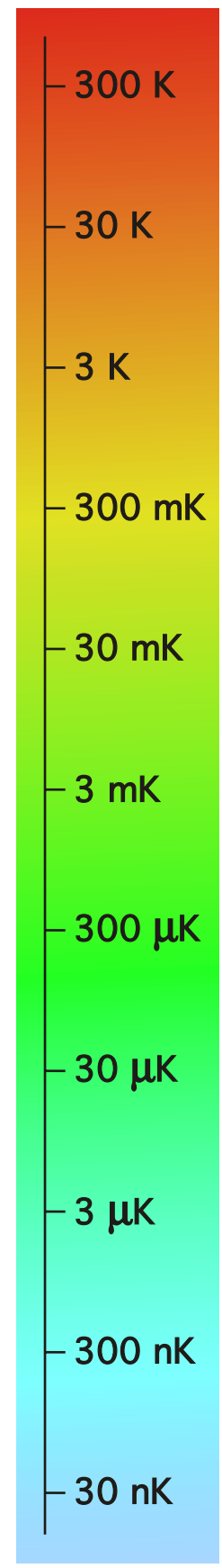
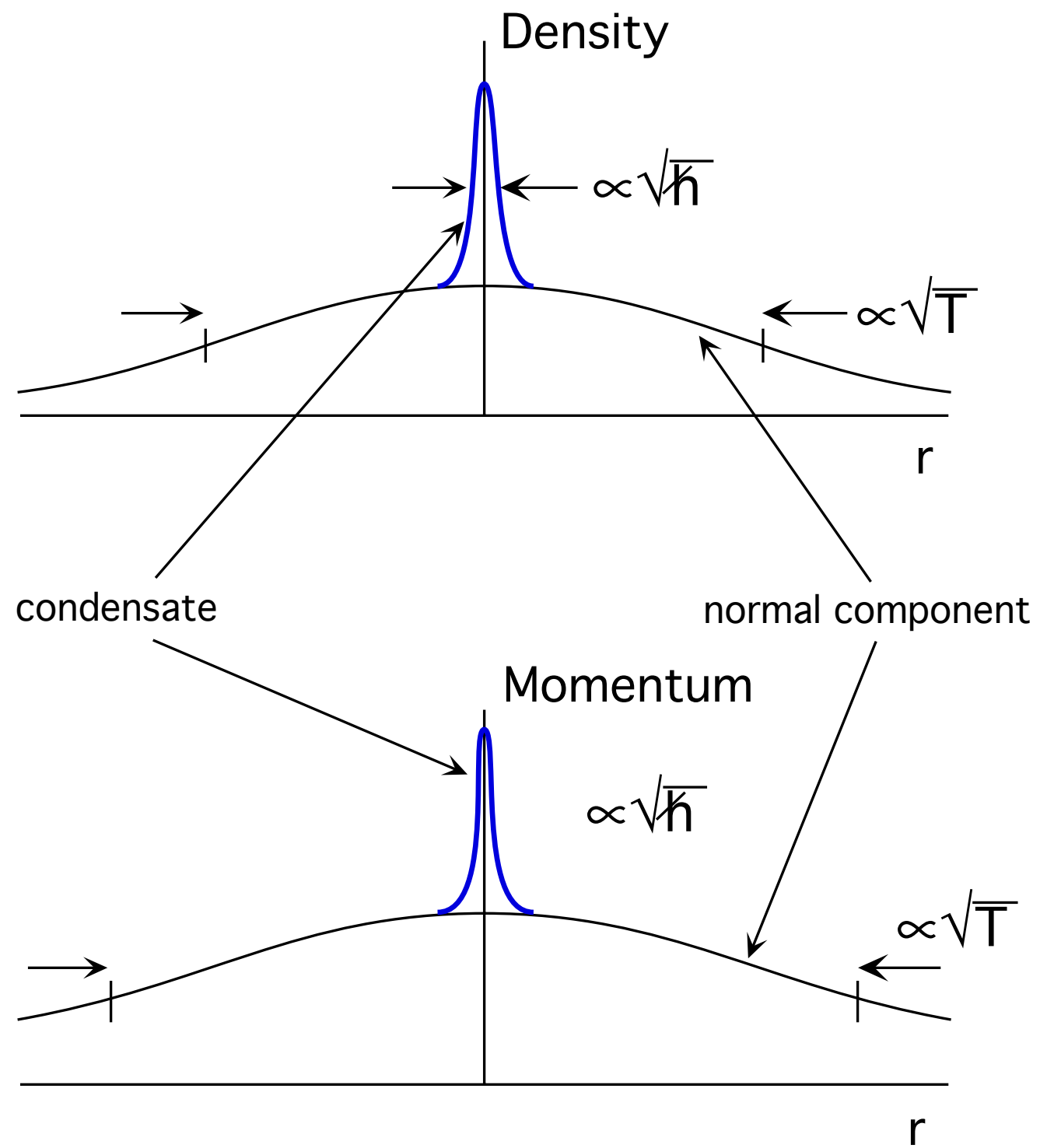
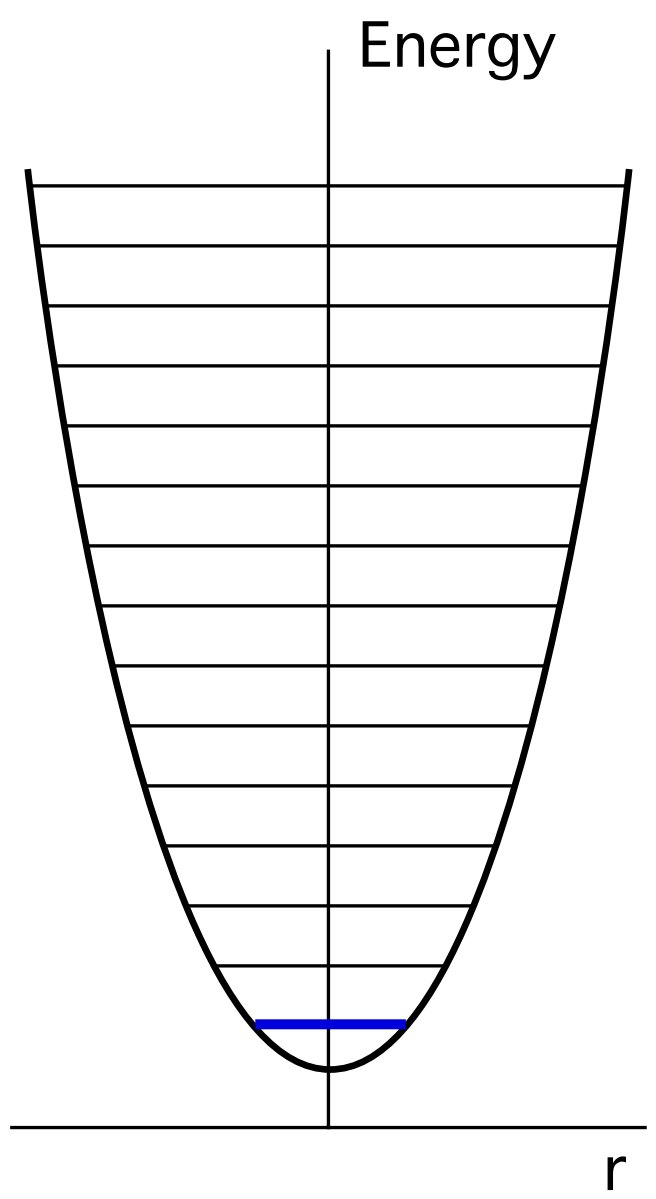




Graphical timeline of the race for BEC removed due to copyright reasons.



Bose-Einstein Condensation in a Parabolic Trap



1900

1920

1940

1960

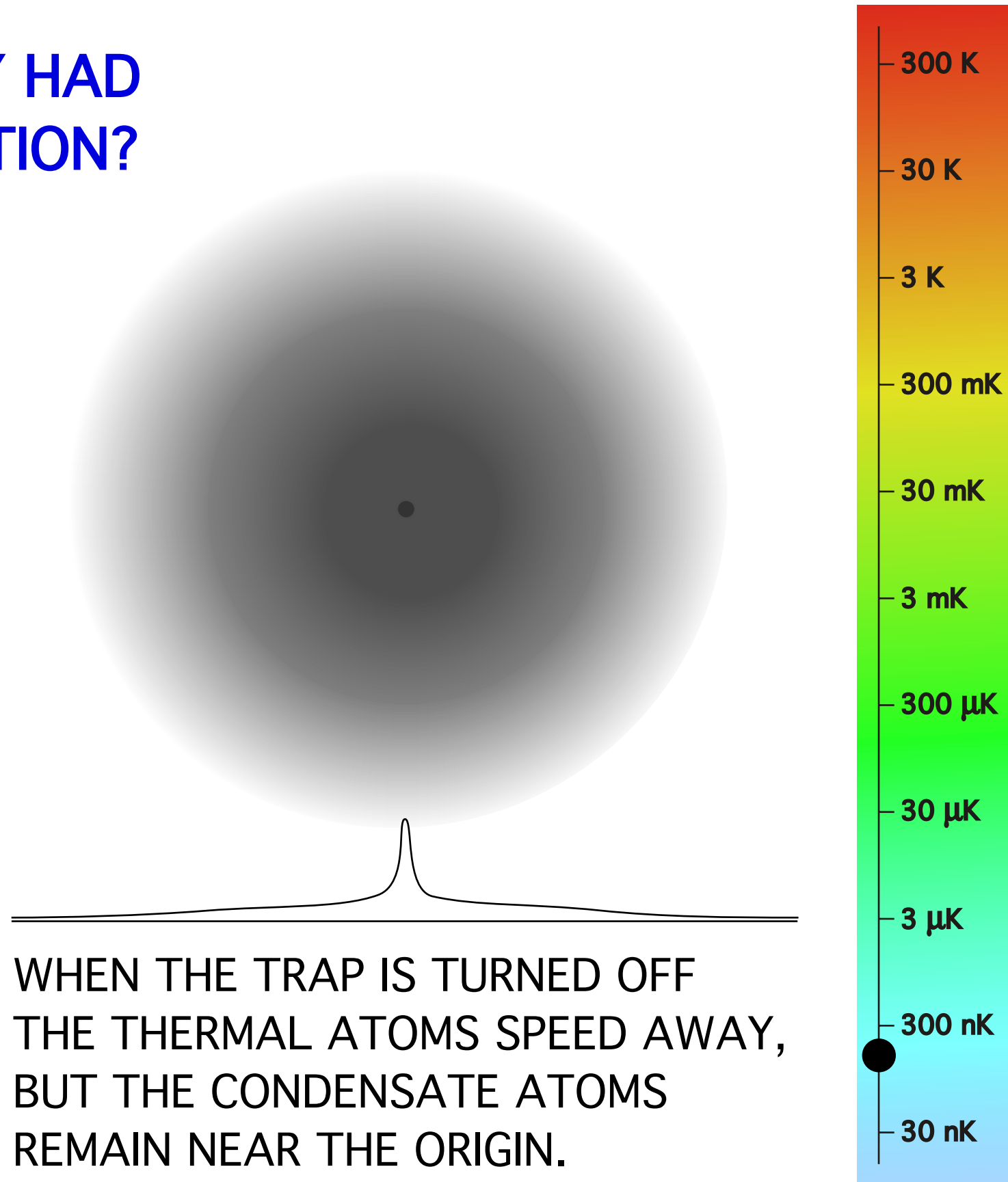
1980

2000

HOW DID THEY KNOW THEY HAD BOSE-EINSTEIN CONDENSATION?

IN THE TRAP, ATOMS IN THE CONDENSATE ARE ALMOST AT REST, THE REMAINDER HAVE THERMAL SPEEDS.

WHEN THE TRAP IS TURNED OFF THE THERMAL ATOMS SPEED AWAY, BUT THE CONDENSATE ATOMS REMAIN NEAR THE ORIGIN.



Cover of *Science* 269 (July 14, 1995) removed due to copyright reasons.



Image of Carl Wieman, Michael Matthews, Michael Anderson, Jason Ensher, and Eric Cornell removed due to copyright reasons.



CARL WIEMAN

MICHAEL ANDERSON

ERIC CORNELL

MICHAEL MATTHEWS

JASON ENSHER



Graphical timeline of the race for BEC removed due to copyright reasons.

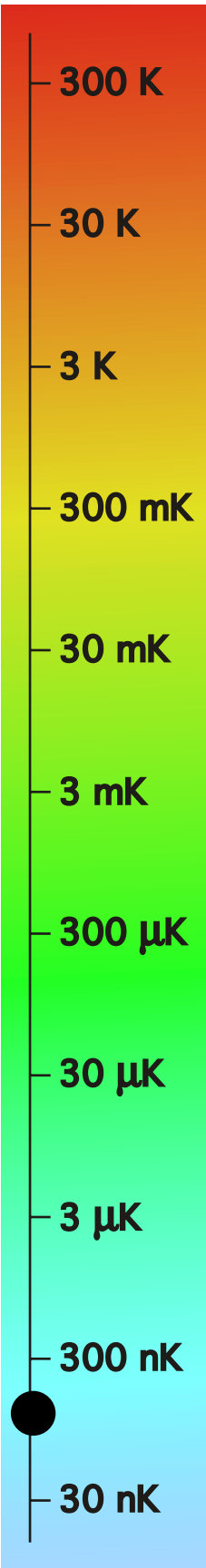
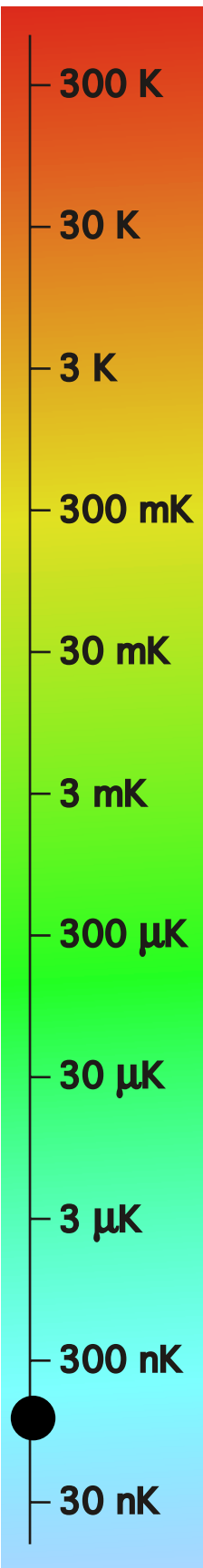




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SUCCESSIVE REAL SPACE IMAGES OF A SODIUM CONDENSATE FORMING IN A KETTERLE TRAP





The Nobel Prize in Physics 2001

Image of the Nobel Prize medal removed due to copyright reasons.

"for the achievement of Bose-Einstein condensation in dilute gases of alkali atoms, and for early fundamental studies of the properties of the condensates"

Image of Eric A. Cornell, Carl F. Wieman, and Wolfgang Ketterle removed due to copyright reasons.

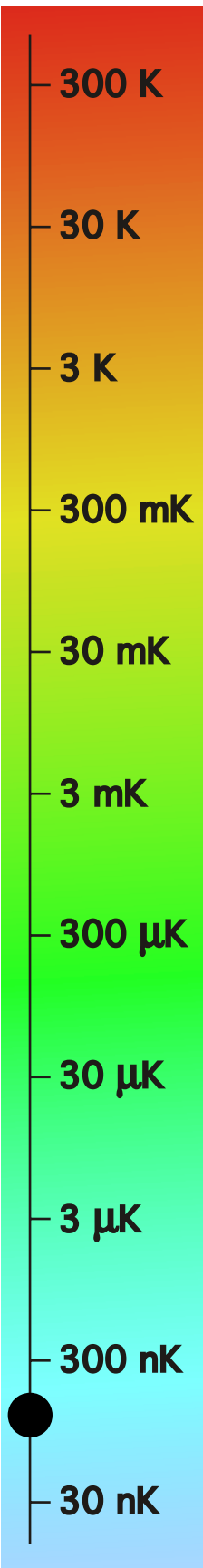


Image removed due to copyright reasons.

WOLFGANG KETTERLE & RANDALL HULET IN STOCKHOLM



Image removed due to copyright reasons.

INTERFERENCE OF MATTER WAVES

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